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WELL PLUGGING APPLICATIONS TO THE INTER-AQUIFER MIGRATION OF SALINE GROUNDWATER IN LEE COUNTY, FLORIDA

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by

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Groundwater Division
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South Florida Water Management District
West Palm Beach, Florida

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SUMMARY

Thousands of free flowing wells, drilled in the 1940's and 50's to supply Florida's agricultural interests, have become sources of saline intrusion into freshwater aquifers throughout the state. Legislation has been passed which addresses the problem by establishing well construction criteria and providing for the disposal of all abandoned flowing wells by January 1, 1992. The South Florida Water Management District joined the other WMD's by establishing a pilot well plugging program in 1979. This program began in Lee County where three freshwater aquifers (the Surficial, Sandstone, and mid-Hawthorn) were being contaminated by uncontrolled wells located throughout the county. The purpose of this program was to: 1) determine methods of saline intrusion related to water wells, 2) establish cost effective methods of plugging flowing wells, 3) prevent the continued loss of fresh water by plugging offensive wells, and 4) determine the effect plugging has on water quality on a local and regional scale. The results of this study are as follows:

1. Three methods of saline intrusion related to well construction have been identified in this report: a) saline water enters the Surficial Aquifer System through seepage adjacent to uncontrolled flowing wells drilled into the Floridan Aquifer System, b) in wells which are valved off at the surface, high pressure water from the Floridan enters the mid-Hawthorn and Sandstone aquifers through uncased portions of the well or through corrosion holes, and c) in coastal areas where the mid-Hawthorn aquifer has been widely developed, the fluctuating saline water table has corroded steel casing below the surface allowing saline water to enter the well and recharge the mid-Hawthorn aquifer.

   In addition, structural offsets in lower Miocene beds were identified in the Estero area of Lee County. These data substantiate similar findings elsewhere in the county presented by other authors and

suggest a possible source of upward saline migration from deep aquifers into the Suwannee aquifer and the lower Hawthorn/Tampa producing zone; No data indicate these faults extend through the lower Hawthorn confining zone.

2. Of the wells surveyed in this report, 26 percent were uncontrolled and flowed freely at land surface. The average discharge from an uncontrolled well was 86 gpm. Only nine percent of the wells contained enough casing to isolate the three shallow freshwater aquifers. The mid-Hawthorn aquifer was directly exposed to the Floridan aquifer in 91% of the wells and both the mid-Hawthorn and the Sandstone aquifers were exposed in 12% of the wells surveyed. The average chloride concentration for the Floridan aquifer was 995 mg/l.

3. A figure of 1850 is proposed for the total number of flowing wells drilled in Lee County. This figure is based on the rate of expansion of the existing USGS inventory and replaces the previous estimate of 3000. Prior to any plugging activities, an estimate of 90 mgd was proposed by Healy (1978) for the amount of water which enters the shallow aquifers from flowing wells in Lee County. This figure is revised to 81 mgd (60 mgd from surface discharge and 11 mgd from internal flow) based on field data collected from this study.

4. The corrosion potential of waters from the Surfical, Sandstone, mid-Hawthorn and Floridan Aquifer Systems were evaluated using the Ryzner stability index and Langelier saturation index. Results indicate that the waters of the Floridan Aquifer System are non-corrosive in a reducing environment and tend to produce protective calcium carbonate scale inside steel casings; however, waters from the shallow artesian systems are more aggressive to steel casings, with corrosion being most intensive in the Surfical Aquifer System. Therefore, observed corrosion of steel casings

in Lee County occurs mostly on the outside of the casing adjacent to the shallow aquifer. In addition to chemical breakdown of casings, sulfur reducing bacteria (Desulfomaculatum) is suspected to be accelerating casing decay. A casing life expectancy of 20 to 25 years has been proposed for steel cased wells constructed without annular grout. The average age of the flowing wells surveyed is 30 years.

5. Several methods of plugging flowing wells were attempted during this study. Stage grouting was found to be the most cost effective. This method involves the emplacement of calculated volumes and weights of slurry between each producing zone in a well. The cost of plugging an "average" flowing well (544 ft deep with 130 feet of six inch casing) from 1979 to 1983 was $1,825.00. The average cost of plugging a mid-Hawthorn well in Cape Coral was $176.06 for the same period. Funding was based on cost sharing cooperatives between the District and various state, county, and municipal agencies.

6. By the end of September 1983, a total of 270 flowing wells were plugged, which prevented an estimated 13 mgd of Floridan Aquifer System water from contaminating the shallow aquifers. An additional 90 flowing wells were reported by the USGS as having been plugged prior to the SFWMD's plugging program. Five hundred and forty two abandoned mid-Hawthorn wells were plugged in Cape Coral under the Cape Coral-SFWMD's plugging program. An additional 593 mid-Hawthorn wells were plugged by the City of Cape Coral alone prior to 1979.

7. The rate at which the water quality in an aquifer recovers from point source contamination depends primarily on the extent of the contamination, the ambient groundwater velocities, and the hydrodynamic dispersion of the contaminant through the invaded aquifer.

Dispersion results in faster dissipation of saline plumes than could be attributed to groundwater flow alone. Water quality recovery will occur faster in heterogeneous sediments such as fractured or solutioned limestones, where dispersion is greatest, and in unconfined aquifers which receive direct recharge. Measurable water quality recovery in confined aquifers in Lee County will occur within a time frame of several years, while significant recovery in an unconfined aquifer will occur within a year depending upon the amount of rainfall. It is too early to identify regional improvements in water quality in the shallow artesian aquifers of Lee County although local improvements have been recorded. The potentiometric surface of the Floridan Aquifer System has shown recovery on a regional scale. Continued increases of the artesian head pressures within the upper zones of the Floridan Aquifer System should prevent further water quality deterioration from deeper sources within that system.

ACKNOWLEDGEMENTS

This project is the result of concerns over the groundwater resources within the boundaries of the South Florida Water Management District. The author wishes to recognize the contributions of the Lee County cooperators whose genuine concern for the groundwater resources of the area will be recognized for years to come: the Lee County Commissioners, the City of Fort Myers, the City of Cape Coral, the East County Water Control District, the Agricultural Stabilization and Conservation Service, and the Lee County Department of Transportation. An inventory of deep wells which formed the basis for long term planning was provided by the U. S. Geological Survey in Fort Myers under the direction of Frank Watkins. Additional site locations and field support were provided by Ned DeVaney, Lee County Department of Environmental Protection Services.

Recognition is given to Edward P. Mosher and the late Bruce Mackelduff for the administrative development and supervision of the project. The magnitude and success of this program is reflective of their efforts. Special thanks are given to Martin C. Braun, Jr. for his contributions in the technical development of the program. His fine work in the field has had a major influence on the program.

This report was prepared under the direction and supervision of Abe Kreitman, former Director, Groundwater Divison, South Florida Water Management District. It was through his efforts that this program was founded, and his continued guidance in all aspects of the study is gratefully acknowledged.

INTRODUCTION

The social and economic growth of Florida is strongly influenced by the extensive groundwater network which supplies fresh water to most of the state. While much of the potable water comes from shallow water table and artesian aquifers, large portions of the state are underlain at depth by extensive limestone aquifers which are under sufficient artesian head to cause wells to flow at land surface. Much of this water is mineralized to a point where it is of little use to man and could pose a threat to potable groundwater if improperly constructed or maintained wells allow this water to enter freshwater aquifers. In 1978, approximately 15,000 wild flowing wells discharged about 790 million gallons of mineralized water in Florida every day (Healy, 1978). Discharge occurs both internally, in wells constructed to tap several water bearing zones of different pressures, and externally, in wells without valves or caps. These problems are most pronounced along the southern coastal regions of the state including, Brevard, Lee, Charlotte, Sarasota, St. Lucie, Hendry, DeSoto, and Hillsborough Counties.

A second source of groundwater contamination occurs in shallow artesian aquifers located beneath intertidal areas. In this case, steel casings, exposed to a fluctuating saline water table have corroded allowing saltwater to leak into the well and recharge the aquifer.

Florida has recognized the need to protect the groundwater resources of the state by establishing well construction standards and plugging procedures. Enactment of these regulations is the responsibility of the Department of Environmental Regulation and the Water Management Districts. The South Florida Water Management District (SFWMD) began its well plugging program in Lee County in 1979. The purpose of this program is to prevent the continued contamination of the freshwater resources by plugging offensive wells. This would be accomplished by: 1) determining methods of saline intrusion related to water wells, 2) establishing cost-effective methods of plugging flowing wells, 3) preventing the continued loss of fresh water by plugging offensive wells, and 4) determining the effect plugging has on water quality on a local and regional scale. By the end of the 1982-83 fiscal year 350 Floridan wells were located and logged, and 270 deep flowing wells and 542 shallow wells had been plugged. This action has prevented the loss of approximately thirteen million gallons of saline water per day from contaminating freshwater aquifers. Due to the continued support of the Lee County cooperators and the Governing Board of the South Florida Water Management District, this program is being continued and expanded into other counties.

Previous Investigations

Development of a state-wide inventory of flowing wells was first undertaken by Hendry and Lavender in 1957 in response to legislation passed in 1953 and 1955. The final report was completed in 1957 by Hendry and Lavender. Details of this inventory are on file with the Department of Environmental Regulation in Tallahassee. In 1978, this inventory was updated by Healy to include estimates of the amount of water discharged by flowing wells both at the surface and internally.

Methods of interaquifer saline migration in Lee County were first presented by Sproul, Boggess, and Woodward in 1972. Evidence of faulting, along with well construction practices, were presented as sources of upward saline migration in the McGregor Isle area. Missimer and Gardner in 1976 used high resolution seismic reflection profiling to investigate the vertical extent of the faults proposed by Sproul. They concluded that no faulting exists above the lower Hawthorn confining zone in the area studied.

In 1974, Boggess evaluated the saline resources of Lee County and presented selected data on 217 flowing wells. A study on the effects of plugging a flowing well on water quality in an unconfined aquifer was presented by Boggess 1973. While the saline plume identified was small (600 feet) recovering to background chloride levels occurred within two years.

The problem of downward saline migration in shallow artesian wells located in the intertidal areas of Cape Coral was introduced by Boggess, Missimer, and O'Donnell in 1977. Several case studies involving saline intrusion related to well construction are outlined in this report.

Description of Study Area

Lee County is located in southwest peninsular Florida between Latitude 26° 19' 04" North and 26° 47' 23" North and Longitude 81° 33' 50" East and 82° 16' 24" East (Figure 1). It is bordered to the north by Charlotte County, to the east by Hendry County, the south by Collier County, and to the west by the Gulf of Mexico. The county is bisected by the Caloosahatchee River which is used for drainage, navigation, and freshwater supply.

Land use patterns in the county have shifted significantly from agricultural to urban in the past 40 years. During the 1940's and 50's Lee County was largely an agricultural region producing winter vegetables, livestock, flowers, and citrus. Agricultural interests were concentrated along the Caloosahatchee River to facilitate shipping. Hundreds of deep wells were drilled into the Floridan Aquifer System to obtain free-flowing irrigation water. Rapid urbanization began in the 1960's and significantly changed the existing land use patterns. The population grew from 54,539 in 1960 to 205,266 in 1980 and is expected to reach 300,000 by 1995. This trend has manifested itself in moderate to high density housing with multifamily housing starts outnumbering single family housing by over 50 percent during 1980 and 1981. The majority of the population is concentrated within 10 miles of the coast and along the Caloosahatchee River. Development has occurred at the expense of agriculture and is reflected in the decline in acreage used for farming. In 1959 a total of 500,000 acres was used for farming. This figure dropped to 107,182 in 1978. As a result, the majority of former irrigation wells are now located in populated urban areas.

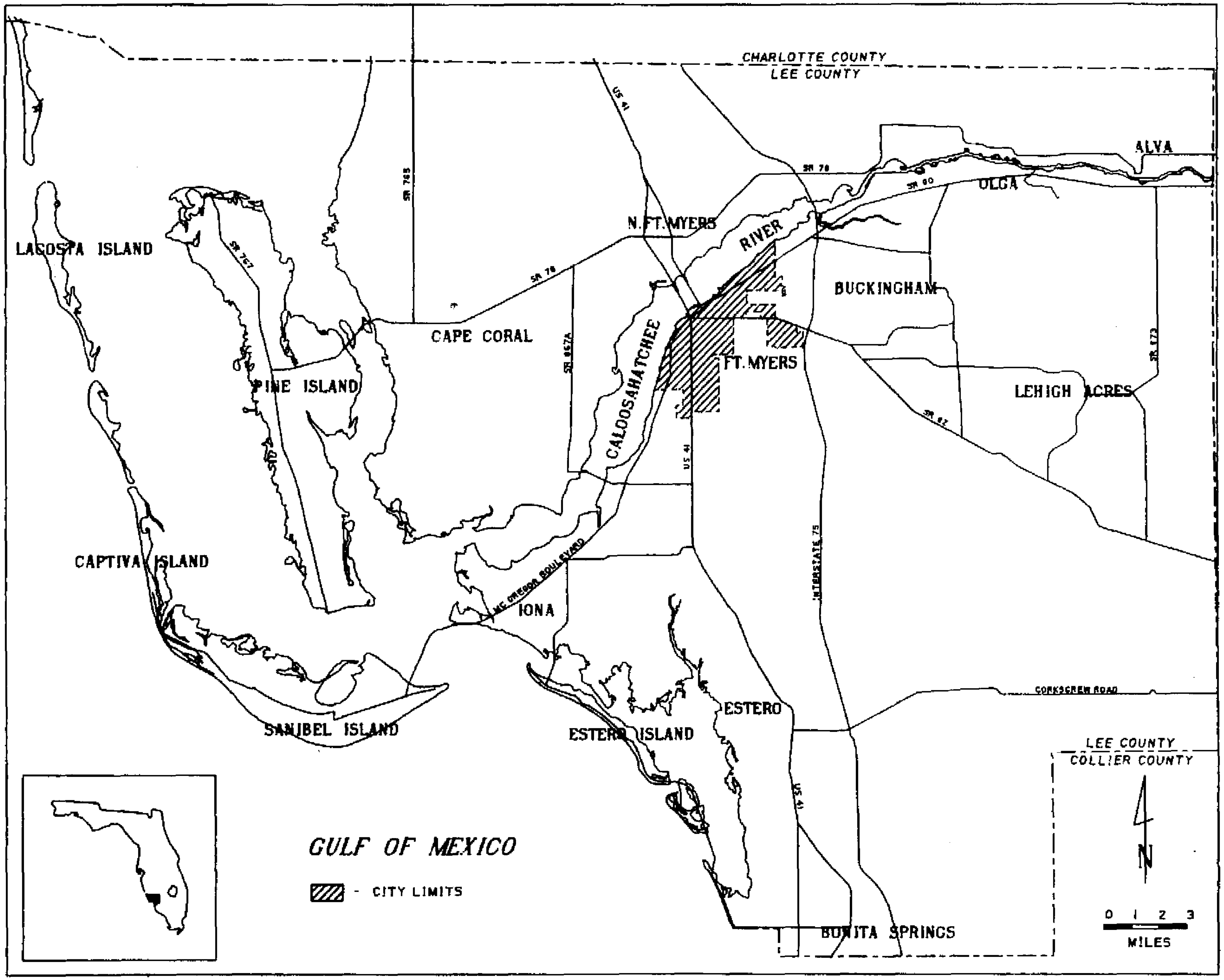


Figure No. 1 LOCATION OF STUDY AREA

HISTORICAL REVIEW OF FLORIDA WELL PLUGGING PRACTICES

Inventories to assess the extent of the flowing well problem were begun in the mid-fifties by several agencies. In 1954, the Florida Association of Soil Conservation District Supervisors began collecting data on flowing wells within their districts. In 1956, the Florida Water Resources Study Commission began a study which expanded the 1954 inventory to include flowing wells throughout the State. The results of these studies where combined in 1957 by the Florida Geological Survey for the State Legislature. A total of 1,883 wild flowing wells were identified (Hendry and Lavender, 1959). Since then, additional inventories have been conducted by the U. S. Geological Survey and the Water Management Districts. The more recent inventories include estimates of wells which allow internal exchange of saline water and are summarized by Healy (1978).

Attempts by the State to regulate uncontrolled flowing wells began in the early 1950's and are outlined by Hendry and Lavender (1959) and Healy (1978). Severe drought conditions in the early 1950's resulted in the passage of regulatory measures to curtail the misuse of artesian wells in Florida. Chapter 370.051-370.055 of the Florida State Statutes (1953), required working valves or caps on all flowing wells. In 1955, the Florida Geological Survey received an appropriation to implement this program. The passage of Chapter 373.021-373.061 F.S. by the Legislature in 1957 provided for the plugging of all artesian wells which were in violation of the law.

Until the early 1970's the regulation and control of abandoned flowing wells was the responsibility of various state and local agencies, along with the individual property owner. In 1972, the Legislature acted to form the five Water Management Districts. In 1974, formal rules and regulations governing water wells in Florida were adopted and implemented under the regulatory responsibility of the Department of Environmental Regulation and the Water Management Districts. Three specific considerations towards abandoned wells were contained in these rules which provided for: (1) the implementation of a permitting system by the Water Management Districts to regulate the plugging of abandoned wells; (2) the elimination of wells which allowed interchange of water between aquifers or the uncontrolled loss of artesian pressure; and (3) the establishment of minimum criteria for the plugging of abandoned wells. In June 1983, the Legislature enacted the "Water Quality Assurance Act of 1983". Part IV of this legislation calls for each of the five water management districts to: (1) accomplish the plugging of all known abandoned wells within the District on or before January 1, 1992; and (2) submit by January 1, 1983 a preliminary inventory and work plan outlining the methods and costs of plugging all known abandoned wells. The Act also establishes 500 mg/l of chlorides as a maximum allowable discharge concentration for flowing wells.

The extent to which the Water Management Districts regulate the plugging of derelict wells varies with each District. The Suwannee River Water Management District (SRWMD) and the Northwest Florida Water Management District (NFWMD) have limited well plugging programs because the problem of saline flowing wells and interaquifer contamination is not widespread in these regions. Well plugging is usually limited to abandoned wells and test holes. Both Districts established well plugging permitting procedures by 1976. The SRWMD requires the owner to submit abandonment plans for permit approval while the NFWMD will provide geophysical logs and prepare technical plugging specifications for the owner, if necessary, at no charge. The cost for plugging a well is generally the responsibility of the property owner in either District.

The Southwest Florida Water Management District (SWFWMD) and the St. Johns River Water Management District (SJRWMD) developed more comprehensive programs which provide funding to those areas where abandoned saline wells pose a much greater threat to freshwater resources. The SWFWMD began its "Quality of Water Improvement Program" (QWIP) in 1974. This program is administered through the Peace River, Manasota, and Alafia Basin Boards which provide funds for plugging. In 1982, the plugging program was active in both the Peace River and Manasota Basins; all known offensive wells in the Alafia Basin had been plugged (Kim Preedom, personal communication, 1982). Wells are plugged to specifications prepared by the SWFWMD which are based on interpretation of geophysical logs. Techniques utilized by SWFWMD for plugging wells include: emplacement of inert fill, conventional cement grouting, and QWIP plugs. The QWIP plug, which was developed by the SWFWMD, is an inexpensive inflatable cement packer used to isolate producing zones. By the end of 1982, SWFWMD had plugged 160 wells throughout the District and capped 208 wells which were uncontrolled but were not found to be a source of interaquifer contamination (Preedom, personal communication, 1982). A number of additional wells were plugged in the District through independent programs developed and funded by Sarasota County and the Department of Transportation.

The St. Johns River Water Management District (SJRWMD) began its cooperative well plugging program in 1976. This program originated as a cost sharing project with the Agricultural Stabilization and Conservation Service (ASCS) to improve the quality of agricultural irrigation wells (Munch, 1978). Under this program problem wells were identified, geophysically logged, and rehabilitated or plugged at no cost to the owner. In 1981 a second cooperative agreement was implemented between SJRWMD and Brevard County to allow privately owned non-agricultural properties to benefit from this program. While wells which qualify under the ASCS-SJRWMD program are generally partially plugged, wells in Brevard are completely plugged using QWIP plugs or conventional cement grouting. Both flowing and nonflowing wells are plugged under this program. At the end of the 81-82 fiscal year, 15 wells had been plugged in Brevard County and approximately 20 wells had been rehabilitated or plugged under the ASCS cooperative program (Doug Munch, personal communication, 1982).

Development of South Florida Water Management District's Well Abandonment Program

Wells which penetrate the Floridan Aquifer System exhibit flowing artesian conditions throughout the boundaries of the SFWMD except in the northern portion of the Kissimmee Planning Area (central Florida) where the Floridan receives recharge. Waters from the Floridan, although often too saline for potable use, are used extensively for agriculture throughout south Florida. Through poor well construction or neglect, thousands of these wells have become sources of contamination to shallow freshwater aquifers through uncontrolled surface discharge or internal flow. Areally, approximately 70 percent of the SFWMD is affected by this problem.

Recognizing this, the SFWMD implemented its own well plugging program in 1978. Prior to this, wells were plugged through the state-wide ASCS program or by local agencies, with the District, the Department of Natural Resources, the Department of Environmental Regulation, and the U. S. Geological Survey providing technical review and support. It was initially established that the plugging program appropriated by the SFWMD's Governing Board would be active in one county while the program developed. Funding was provided to purchase a Gearhart-Owens Widco Model 3200 geophysical well logger which would provide technical data necessary to develop effective plugging techniques. Administrative work began to locate a study area, appoint a staff, and prepare the legal agreements needed for the program. The Well Abandonment Program formally began in August of 1979 with the logging of well WA-1 in Lee County.

In selecting the county to begin the plugging program, consideration was given to: (a) the type and extent of the problem caused by abandoned wells,

(b) the number of offensive wells available for plugging, (c) the availability of an accurate inventory, and (d) selecting an area where maximum social and economic benefit could be derived from the program. A state-wide inventory of uncontrolled flowing wells, prepared by the U. S. Geological Survey, identified five counties in the District with more than 200 uncontrolled flowing wells: St. Lucie, Okeechobee, Glades, Hendry, and Lee Counties.

Virtually all wells which penetrate the Floridan Aquifer System in St. Lucie County will flow at land surface. Healy (1978) reported that over 400 of these wells were uncontrolled and were discharging 48 million gallons per day (mgd). Chloride concentrations for the Floridan Aquifer System in St. Lucie County range from 200 mg/l in the southwest to over 1400 mg/l in the west central portion of the county (Brown and Reece, 1979). Chloride values in excess of 1000 mg/l occur along a "ridge" which trends from southeast to northwest and along the northeastern coastal region. Surface discharge and internal flow in these regions have reportedly caused localized contamination of the shallow freshwater aquifer. As St. Lucie County is rapidly changing from a primarily agricultural region to an urbanized area, it is anticipated that the problem of saline flowing wells will become more acute as development progresses.

Approximately 350 uncontrolled wells discharge over 50 mgd in Okeechobee County (Healy, 1978). These wells occur in the southern portion of the county where the potentiometric surface of the Floridan system exceeds land surface. Chloride concentrations are generally low in the north portion of the county and increase to the southeast with the 500 mg/l isochlor located within ten miles of the north shore of Lake Okeechobee (Shaw and Trost, 1984). Most wells are used for irrigation, and requests for plugging or rehabilitation are usually directed through the ASCS by landowners wishing to improve the quality of their wells.

A total of 650 wells (250 in Glades County and 400 in Hendry County) discharge approximately 78 mgd through internal and surface flow in Glades and Hendry Counties (Healy, 1978). Wells drilled into the Floridan Aquifer System will generally flow throughout both counties with potentiometric heads often in excess of 30 feet above land surface. Water quality is generally poor with chloride values ranging from less than 100 mg/l to 4,240 mg/l (Klein et al, 1964). A problem of uncontrolled saline discharge extending into both counties near the City of LaBelle has been documented by Klein and others (1964). The study identified seven deep wells, ranging in depth from 600 to 800 feet and constructed with 80 feet of steel casing, to be the source of the contamination. Most shallow, freshwater wells in the area were developed in a shelly limestone located between 60 and 120 feet below land surface. Differential pressure between the Floridan and the shallow aquifer resulted in internal flow which formed a contaminant plume of saline water over two miles long and three quarters of a mile wide across LaBelle and north into Glades County. Both counties depend on shallow groundwater for potable supply and, although neither county is heavily populated, local contamination of the shallow aquifer is becoming a widespread threat to the potable groundwater.

The problem of saline intrusion related to well construction is best documented in Lee County where three freshwater aquifers are being contaminated by abandoned wells. Detailed investigations on the effects of saline wells in Lee County have been presented by several authors including Sproul, et al. (1972), Boggess (1973 and 1974), and Boggess, et al. (1977). An estimate of 2,500 to 3,000 deep artesian wells was proposed by Sproul in 1972 for Lee County. These wells discharge internally into freshwater aquifers or flow freely at the surface. This, combined with downward leakage of seawater through corroded casings in shallow coastal aquifers, has had widespread effects on fresh groundwater resources.

Details from an inventory of 742 flowing wells, collected by the U.S. Geological Survey (USGS) were made available to the SFWMD. This inventory included data on both test and monitoring wells in addition to abandoned wells. Ninety of the wells were known to be plugged and 50 wells belonged to the USGS monitoring network. Most of the remaining wells would qualify for plugging under the District's program. The population growth and rapid development of Lee County was also considered, as the problem of limited freshwater resources was beginning to threaten future growth. Because of the magnitude of the problem, the immediate threat posed by saline wells, and the availability of detailed information regarding the problem, the District began its well plugging program in Lee County.

It was decided that a cooperative program similar to that used by the St. Johns River WMD would be the most cost effective method for plugging a large number of wells in a short period of time. The District agreed to extend the scope of the cooperative program to include federal, county, or municipal agencies in order to diversify the program. The initial cooperative agreements consisted of a labor and cost sharing arrangement. The District's responsibility included providing manpower and equipment to geophysically log the wells, preparing plugging specifications, inspecting the actual plugging procedure, and paying for half the cost of the plugging. The county cooperator would locate and prepare each well site for logging and plugging, administer the plugging contract, and pay half the plugging fees. Contractors were selected through competitive bidding on a time and materials basis.

All flowing wells logged and plugged in the SFWMD's program are located either through the inventory furnished by the USGS or through public relations campaigns. The use of television, newspapers, and seminars to various civic associations have proven most useful in expanding the existing flowing well inventory. Additional well locations have been provided by property owners during plugging operations and by SFWMD field crews. By the end of 1983, the locations of approximately 60% of the flowing wells surveyed were provided as a result of public relations campaigns.

After the wells are located, the owners are notified and requested to sign a waiver which allowed their wells to be logged and plugged. In many cases, the owners live out of the county and have to be located through the county tax records. Once the waiver has been signed and the well logged, it is assigned a priority based on the degree of interaquifer connection, the salinity of the well, the flow rate, and the proximity to potable supply wells.

Details regarding the locations of the wells which have been logged and plugged, along with details regarding the administration of the plugging program, are presented in Appendix I and II. The locations of shallow wells associated with the Cape Coral plugging program are not included.

During the 1979-80 fiscal year the District established cooperative agreements with Lee County and the East County Water Control District which represents Lehigh Acres. A third coop was established with the City of Cape Coral to plug two inch shallow wells. These shallow wells do not require any special grouting techniques, and therefore, the City of Cape Coral agreed to administer all aspects of this program with the District supplying funding only. Under these arrangements 95 flowing wells were located and logged, 24 flowing wells were plugged, and 175 shallow wells in Cape Coral were plugged. In 1980, the Lee County Department of Transportation joined the program in order to plug wells under roads or along right-of-ways. During the 1980-81 fiscal year a total of 59 wells were logged, 43 flowing wells and 149 shallow wells were plugged. In 1981 the Agricultural Stabilization and Conservation Service (ASCS) and the City of Ft. Myers expanded the program to include six cooperators. The ASCS agreed to pay 75% of the plugging cost for wells on agricultural properties while the District would administer the contract and provide 25 percent of the plugging cost. The agreement with the City of Ft. Myers was an equal cost sharing agreement pertaining to flowing wells within the city limits. During the 1981-82 fiscal year 100 wells were logged, and 98 flowing wells and 157 shallow wells were plugged. All existing cooperative agreements were extended into the 1982-83 fiscal year; however, due to manpower shortages experienced by most of the cooperators, the District provided additional manpower to locate and prepare the well sites. As a result, the cost sharing agreements with the Lee County, ECWCD, the City of Cape Coral, and the City of Ft. Myers were modified from a dollar per dollar agreement to a 60-40 agreement with the District paying 40 percent of the plugging cost. During this fiscal year, 96 wells were logged, 105 flowing wells and 120 shallow wells were plugged.

HYDROGEOLOGY OF LEE COUNTY

In developing a regional well abandonment program it is necessary to obtain an accurate understanding of the hydrogeology of the study area. Aside from aquifer delineation, data on ambient water quality, potentiometric head and local and regional hydraulic gradients are necessary for each producing zone. Such knowledge is fundamental in developing theories on the methods of saline intrusion which in turn provide the criteria for well abandonment techniques.

Since the objective is to isolate aquifers during abandonment, aquifer delination is of primary importance. Information on regional extent, structural elevation, thickness, and degree of confinement is necessary for each aquifer. In units with interbedded producing and confining zones, the degree of hydraulic connection and variance in water quality between the producing zones must be defined. Ambient water quality of each aquifer is useful in quantifying the degree and areal extent of intrusion caused by a saline well. Offensive wells can often be located from the contaminant plume in areas of anomalously poor water quality. Factors affecting the configuration of the plume include the permeability of the invaded zone, the differential head pressures between the saline and freshwater aquifer, and the hydraulic gradients within the invaded zone. Potentiometric pressures of flowing wells are also necessary to calculate slurry weights of the well plugs.

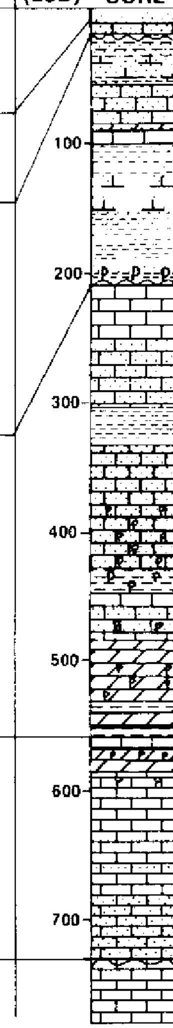
The rocks underlying Lee County have been grouped into three major hydrogeologic systems based on their spatial relationship in the stratigraphic column (Figure 2). These include the Surficial Aquifer System, the Hawthorn Aquifer System, and the Floridan Aquifer System (Wedderburn, et al, 1982). These systems are further divided into aquifers and confining zones based on the degree of vertical and lateral hydraulic conductivity within each rock

STRATIGRAPHY

SYSTEM	SERIES	FORMATION	MEMBER		LITHOLOGY
QUATERNARY	HOLOCENE / PLEISTOCENE	UNDIFFERENTIATED	UNDIFFERENTIATED		Medium to fine grained subangular quartz sand with varying amounts of shell and clay. The lower section consists of loosely consolidated biomicrites and shell beds
TERTIARY	PLIOCENE	TAMIAMI	Ochopee Lm. Bucking. Lm. Pinecrest Sd.		Sandy biogenic calcarenite with minor sparry calcite and dolomite. Silt size phosphate up to 5% highest concentrations at the base.
TERTIARY	MIOCENE	HAWTHORN	UPPER MEMBER	LaBelle Clay Alva Clay Lehigh Acres Sandstone	Predominantly clastic sediments including clay, silt, sandstone, and shell beds with occasional interbedded sandy biogenic limestones. Varying percentages of silt to pebble size phosphate throughout with highest concentrations (25%) occuring at the base of the unit
TERTIARY	MIOCENE	HAWTHORN	LOWER MEMBER	Undiff.	Predominantly carbonate sediments including phosphatic limestones and dolomites interbedded with dolosilt and clay.
TERTIARY	MIOCENE	TAMPA LIMESTONE	Undiff.		Light orange biogenic limestones and dolomites containing up to 10 percent quartz sand and silt size phosphorite. Increased quartz sand occurance at base of unit.
TERTIARY	OLIGOCENE	SUWANNEE LIMESTONE	Undiff.		Medium grained biogenic calcarenite with minor percentages of quartz sand and phosphate

HYDROGEOLOGY

DEPTH (LSD) / LEO28 CORE



SYSTEM	UNIT
Surficial Aquifer System	Unconfined
	Semi-confined
HAWTHORN AQUIFER SYSTEM	UPPER HAWTHORN CONFINING ZONE
	SANDSTONE AQUIFER
	MID-HAWTHORN CONFINING ZONE
	MID-HAWTHORN AQUIFER
	LOWER HAWTHORN CONFINING ZONE
FLORIDAN AQUIFER SYSTEM	LOWER HAWTHORN/ TAMPA PRODUCING
	SUWANNEE AQUIFER

Figure No. 2 GENERALIZED HYDROSTRATIGRAPHIC COLUMN FOR LEE COUNTY, FLORIDA

unit. The Surficial Aquifer System for much of Lee County is characterized as a water table aquifer; however, in those areas where calcareous clay beds are present in sufficient thickness to act as semi-confining beds, the System is divided into two separate producing zones. The Hawthorn Aquifer System consists of two aquifers; the Sandstone aquifer and the mid-Hawthorn aquifer, and three semi-confining zones; the upper Hawthorn, the mid-Hawthorn, and the lower Hawthorn. The Floridan Aquifer System is composed of the lower Hawthorn/Tampa producing zone, the Suwannee aquifer and deeper aquifers here left undifferentiated. All aquifers, with the exception of the water table aquifer, are confined to varying degrees and under artesian pressures. Water quality varies with depth and distance from primary recharge zones.

Surficial Aquifer System

The Surficial Aquifer System as described by Wedderburn, et al. (1982) occurs within the permeable sediments of the here undifferentiated terrace deposits of Pleistocene to Holocene age, and within the Tamiami Formation of Pliocene age. The System is regionally extensive throughout Lee County. The undifferentiated terrace deposits consist predominantly of unconsolidated quartz sand, shell beds, calcareous clays and numerous interfingering limestones. The underlying Tamiami Formation is principally composed of sandy biogenic limestones. The Surficial Aquifer System is unconfined throughout the county except in local areas where calcareous clays, are present in sufficient thickness to act as semi-confining zones. Here, the System is divided into a water table and a semi-confined artesian aquifer. The calcareous clays and dolo-silts of the upper member of the Hawthorn Formation form the lower boundary of the Surficial Aquifer System. The Surficial Aquifer System ranges in thickness from less than 25 feet to over 125 feet. It is thinnest in central Lee County corresponding to a structural high in the underlying Hawthorn Formation, and thickens to the west and southeast.

Water levels for the Surficial Aquifer System generally conform to the topography of the area and respond dynamically to direct recharge as well as to variations in atmospheric pressure. The major source of recharge into the aquifer is rainfall, with additional inflow from surface water bodies and surface discharge from deeper wells. Discharge occurs through evapotranspiration, outflow to surface water bodies and the Gulf of Mexico, and downward leakage across semi-confining zones. Regional flow patterns are controlled by two major recharge areas and by the major outflow basins. In northern Lee County, groundwater in the Surficial Aquifer System flows south from the Telegraph Swamp Area in Charlotte County to the Caloosahatchee River. In southern Lee County, surficial groundwater flows radially from the Immokalee Rise, south of Lehigh Acres, to the Caloosahatchee River and the Gulf of Mexico. Maximum hydraulic gradients occur along the outflow basins.

Water quality for the Surficial aquifer varies widely with distance from the major recharge zones and from the saltwaters of the Gulf of Mexico. Chloride concentrations for the mainland seldom exceed potable supply limits (250 mg/l) with chloride concentration below 50 mg/l at the two major recharge areas. Salinity increases greatly across the fresh-saltwater interface in coastal areas where chloride concentrations in excess of 10,000 mg/l are common.

Sandstone Aquifer

The Sandstone aquifer, as described by Wedderburn, et al. (1982), is the upper water bearing unit in the Hawthorn Aquifer System. It occurs within the permeable sediments of the upper member of the Hawthorn Formation and is of Miocene Age. The aquifer is regionally extensive throughout most of Lee County except in the Cape Coral area and in the extreme northwest corner of the county where the unit is absent. The Sandstone aquifer is composed of sandstones, biogenic limestones, and sandy dolomites. Porosity is mostly intergranular and moldic. The top of the aquifer occurs between -20 and -170 feet NGVD with the thickness of the unit ranging from zero to 200 feet. The unit is thinnest adjacent to Cape Coral and thickens to the east.

The sandstone aquifer is semi-confined above by the upper Hawthorn confining zone which is composed of clayey dolo-silts of low permeability. The aquifer is confined below by the sandy phosphatic dolo-silts of the mid-Hawthorn confining zone. In eastern Lee County the mid-Hawthorn confining zone is bisected by a poorly indurated, sandy, micritic limestone. The areal extent of this unit is not known but has been identified from cuttings in Buckingham and Lehigh Acres. Post, Buckley, Schuh & Jernigan (1978) identified this unit in the Corkscrew Swamp area (southeastern Lee County), informally referring to it as the twelve mile slough limestone. While not developed for municipal supply, the aquifer does produce fresh water to single family homes in these areas.

The configuration of the potentiometric surface of the Sandstone aquifer generally parallels the water levels of the Surficial aquifer. Highest groundwater elevations occur in east central Lee County along SR 82 and in the north central portion of the county along the Charlotte County line. Potentiometric lows occur along the Caloosahatchee River and adjacent to the Green Meadows Wellfield in south central Lee County. Recharge to the Sandstone aquifer occurs mainly by downward leakage across the overlying semi-confining zone and from subsurface inflow from adjacent areas. Discharge occurs by migration across semi-confining zones, subsurface outflow, and by withdrawals due to well pumpage. Hydraulic gradients are generally less than one foot per mile. Maximum gradients, less than 5 feet per mile, occur at the Green Meadows Wellfield. Regional flow patterns radiate from potentiometric highs and generally parallel the flow in the Surficial aquifer.

The salinity of the aquifer rarely exceeds potable supply limits. Chloride concentrations in excess of 250 mg/l occur in northeast and southwestern Lee County. Values below 50 mg/l occur south of SR 82 in the south central portion of the county and correspond to the major recharge area. Chloride concentrations have been measured in excess 700 mg/l in areas where the aquifer receives recharge from waters of the Floridan Aquifer System.

<u>Mid-Hawthorn Aquifer</u>

The mid-Hawthorn aquifer, as defined by Wedderburn, et al. (1982), is the lower water bearing unit of the Hawthorn Aquifer System. It occurs within the permeable sediments of the lower member of the Hawthorn Formation and is of Miocene Age. The aquifer, which consists primarily of sandy biogenic limestones, is regionally extensive throughout all of Lee County. Porosity is mostly intergranular and moldic. Missimer (1978) described a regional disconformity at the contact between the limestones that form the aquifer and the overlying confining beds. The aquifer is confined below by interbedded phosphatic dolo-silts and low porosity limestones. The top of the aquifer occurs at -100 feet NGVD in central Cape Coral and dips radially to over -300 feet NGVD in northeastern and southeastern Lee County. The unit rarely exceeds 75 feet in thickness throughout the county.

The potentiometric surface of the mid-Hawthorn aquifer generally trends from northeast to southwest with a major depression occurring from western Cape Coral to southern Ft. Myers. Highest potentiometric elevations occur in northeastern Lee County where water levels exceed 10 feet above land surface. The lowest potentiometric levels are encountered in a large depression associated with the Cape Coral and Florida Cities wellfields, with water levels greater than 50 feet below NGVD. Hydraulic gradients are steepest along this depression and often exceed 10 feet per mile. Recharge into the mid-Hawthorn aquifer occurs through subsurface inflow from adjacent areas and from artificial recharge from Floridan wells. Discharge from the aquifer occurs from subsurface outflow and discharge from wells tapping the aquifer.

Water quality varies widely for the mid-Hawthorn aquifer but is generally more mineralized than the waters of the Sandstone or Surficial aquifers. Chloride concentrations in excess of 1000 mg/l occur in the island system along the west coast and decrease to the east. The apparent deterioration of water quality in western Cape Coral may be related to a loss of potentiometric head associated with high pumpage rates. East of the Caloosahatchee River chloride concentrations are generally below 250 mg/l; however, values in excess of 800 mg/l have been measured adjacent to salty flowing wells.

Lower Hawthorn/Tampa Producing Zone

The lower Hawthorn/Tampa producing zone, as described by Wedderburn, et al. (1982), is the upper water bearing unit in the Floridan Aquifer System. It occurs within the permeable sediments of the lower carbonate member of the Hawthorn Formation and is of lower Miocene age. The aquifer consists of sandy biogenic limestones and crystalline dolomites with primarily moldic and intercrystalline porosity. The unit is regionally extensive throughout Lee County. The aquifer is confined above by the lower Hawthorn confining zone and below by tight, well indurated sandy micrites. The overlying confining beds consist of poorly indurated limestone and phosphatic dolo-silts; however, in western Lee County several well indurated porous limestones exist within the confining unit that are capable of producing large quantities of water. Missimer (1979) described two of these zones (Hawthorn Aquifer System, Zone 2 and 3), however, the regional extent of these units are limited to the west coastal region of the county. The micrites that form the lower confining zone of the lower Hawthorn/Tampa producing zone vary in the degree of vertical hydraulic conductivity but are generally considered to be semi-confining in nature. The elevation to the top of the unit is between -350 to -650 feet NGVD with the thickness ranging from 75 to 250 feet. The unit is thinnest in the Telegraph Swamp area of north Lee County and thickens rapidly to the south.

The potentiometric surface of the lower Hawthorn/Tampa producing zone trends from northeast to southeast and generally parallels the potentiometric surface of the mid-Hawthorn aquifer prior to development. The potentiometic surface is above land surface throughout Lee County and wells which tap this unit flow freely at the surface. Highest potentiometric head levels, exceeding +50 feet NGVD, are measured in northeastern Lee County. As indicated by the high potentiometric surface of the unit, recharge to the producing zone occurs primarily as subsurface inflow from adjacent areas or upward leakage from deeper sources. Principal discharge occurs by subsurface outflow and from wells which tap this aquifer for agricultural and industrial use.

Water quality for the lower Hawthorn/Tampa producing zones generally exceeds potable supply standards throughout the county; however, the unit is extensively used to supply water for agricultural demands. In addition, Cape Coral, Pine Island, and Sanibel use water from this aquifer and the Suwannee aquifer to supply raw water to reverse osmosis plants. Chloride concentrations range from 250 mg/l to more than 5,000 mg/l.

The Suwannee Aquifer

The Suwannee aquifer is the second water bearing unit within the Floridan Aquifer System. It occurs within the permeable sediments of the Suwannee Limestone which is of Oligocene Age. The Suwannee Limestone is lithologically complex, being composed of medium-grained biogenic limestones interbedded with dolomites, fine grained poorly indurated limestones, and sandstones. The aquifer is regionally extensive throughout Lee County. Due to the thickness of the Suwannee limestone and the existence of interbedded micrites of low permeability, the aquifer is divided into several minor producing zones; however, the major water bearing zones occur near the contacts at the top and the base of the unit. Porosity is mostly intergranular and moldic. The top of the aquifer occurs between -550 to -800 feet NGVD. A structural high occurs in the northeastern portion of the county from northern Lehigh Acres to Buckingham. The water quality of the aquifer is best in this area. The thickness of the aquifer ranges from 350 to 600 feet.

Little information regarding potentiometric head of the Suwannee aquifer is available. Flow, temperature, and fluid resistivity logs from four wells east of the Iona District (WA-156, WA-158, WA-162 and WA-171) indicate production from each of the wells is solely from the Suwannee aquifer. Potentiometric levels for these wells taken in January 1982 were +10, +14, +6 and +11 feet NGVD, respectively. Chloride concentrations ranged from 601 to 805 mg/l. Wells WA-134 and WA-144, which are approximately one mile away, produced water solely from the lower Hawthorn/Tampa producing zone and had head levels of +18 and +21 feet NGVD, respectively (chloride concentration 4,400 and 5,520 mg/l), suggesting that in this area, head levels are lower for the Suwannee aquifer than the overlying producing zones. However, in most areas in the county, the potentiometric surface of the Suwannee aquifer is thought to equal or exceed that of the lower Hawthorn/Tampa producing zone.

Direct water quality data from the Suwannee aquifer is scarce; however, specific conductance data gathered by point samples and geophysical methods (Wedderburn, et. al. 1982) indicate that water quality is generally poorer in the Suwannee aquifer compared to water quality in the overlying aquifers. Chloride concentrations range from less than 600 mg/l in Lehigh Acres to over 10,000 mg/l near the base of the aquifer.

INTER-AQUIFER MIGRATION OF SALINE WATER IN LEE COUNTY

Saline intrusion occurs as saltwater of a given potential migrates into a freshwater body of lower potential. In groundwater, this movement can progress through natural low permeability layers providing there is sufficient difference in potential between aquifers, or it can occur along failures in a confining zone which are caused by faults or uncased well bores. In the study area, mineralized water migrates both upward, from the Floridan Aquifer System into the shallow artesian aquifers, and downward, from leaky wells located along brackish intertidal canals adjacent to developments. In both cases, early well construction practices have resulted in multi-aquifer connections along open boreholes or through corrosion failures in the casing. Well abandonment techniques are based on a detailed understanding of saline movement within a well.

Well Construction

Beginning in the early 1940s, Lee County began to develop its agricultural industry. The availability of free flowing water, year long, combined with the temperate climate, allowed the winter vegetable crop to flourish. Early deep well drilling practices resulted in the development of hundreds of wells which were constructed with minimum lengths of casing prone to corrosion and which have provided direct connection between the Floridan and shallow freshwater aquifer systems.

Prior to 1970, virtually all wells drilled in south Florida were constructed with cable tool drill rigs. This method of drilling utilized percussion action to cut the borehole. Cuttings were removed with a bailer. Casings were driven in place as the well was being drilled. Due to the impact stress inherent in the process of setting the casing, black steel or galvanized pipe was most often used. This structural stress acts to promote the formation of galvanic cells which promote corrosion. Well casings were not grouted in place due to the absence of annular space inherent to this method of drilling. As a general rule the casing was terminated in a competent rock unit and the remainder of the well was left open hole. The well bores of these older wells are frequently tortuous, especially at clay-limestone interfaces, where rapid drilling resulted in deflections of the drilling bit at density interfaces. This frequently results in difficulty with setting tremie pipe and logging the well.

In wells drilled into the Sandstone or mid-Hawthorn aquifers, the casings were set a few feet into the top of the aquifer and the remaining portion of the well was completed to the base of that aquifer. However, in wells which tapped the Floridan Aquifer System, casings were generally terminated hundreds of feet above the top of the Floridan System. Steel casing, especially during war years, was the most expensive part of the well construction. As a result, deep wells drilled into the Floridan were usually cased to the top of the mid-Hawthorn aquifer and the remainder of the well was left open hole. Well construction data collected in Lee County are summarized in Table 1. Geophysical data collected from 147 Floridan wells indicate that only nine percent of the wells were constructed with enough casing to isolate the mid-Hawthorn and Sandstone aquifers. The mid-Hawthorn aquifer was directly exposed to the Floridan Aquifer System in 91 percent of the wells. Both the Sandstone and mid-Hawthorn aquifers were not cased off in twelve percent of the wells. The average well depth was 656 feet. This value differs from the figure quoted for the average well depth plugged given in the appendix due to the number of shallow non-flowing wells plugged under that program. The average flow rates calculated from 205 wells surveyed was 173 gpm. The average chloride concentration was 995 mg/l. All the wells surveyed were drilled with a cable tool rig. The average age of a Floridan well in Lee County is approximately 30 years.

Casing Diameter:	3 in.	4 in.	5 in.	6 in.	8 in.
Number of Samples	6	56	39	101	8
Frequency	2.8%	26.7%	18.6%	48.1%	3.8%

Casing Depth:	<100 ft.	101 - 200 ft.	>201 ft.
Number of Samples	10	128	9
Frequency	6.8%	87.1%	6.1%

Flow Rate:	<50 gpm	51-100 gpm	101-250 gpm	251-500 gpm	>500 gpm
Number of Samples	66	45	41	43	10
Frequency	32.2%	22.0%	20.0%	21.0%	4.8%

Number of wells cased past the mid-Hawthorn aquifer: 13, Frequency: 8.9%.

Number of wells with the mid-Hawthorn aquifer exposed: 134, Frequency: 91.1%.

Number of wells with the Sandstone and mid-Hawthorn exposed: 17, Frequency: 11.6%

Number of uncontrolled flowing wells: 44 (169 wells surveyed), Frequency: 26.0%.

Average casing depth: 148 ft. (147 wells surveyed).

Average well depth: 656 ft. (154 wells surveyed).

Average flow rate: 173 gpm (205 wells surveyed).

Average flow from uncontrolled flowing wells: 86 gpm.

Average chloride concentration: 995 mg/l (193 wells surveyed).

TABLE 1. WELL CONSTRUCTION DETAILS FROM SELECTED WELLS IN LEE COUNTY.

In more recent years, rotary drilling methods have dominated the deep well construction industry. This method of drilling utilizes rotational cutting action instead of percussion to cut through rock. Cuttings are continuously removed by either fluid (hydraulic rotary) or air (air rotary). In general, steel casings have been replaced with less expensive PVC pipe. In 1974, the State of Florida required all casing set by rotary rigs must be cemented in place from top to bottom unless otherwise specified (Administrative Code, Chapter 17-21.10 (2d)). This same legislation (Chapter 17-21.10(2c)) prohibits the construction of wells which allow inter-aquifer exchange. With the passage of this legislation, combined with a greater awareness of the problems generated by past well construction practices, few wells drilled since 1974 have resulted in inter-aquifer contamination.

Corrosion Processes

Perhaps the most significant cause of saline intrusion in the Sandstone aquifer, and a major contributor to contamination of the Surficial Aquifer System, is casing corrosion. Early well construction practices, combined with the chemical nature of groundwater, produce a corrosive environment to steel casings throughout the county. Although the causes vary, corrosion occurs in both shallow and deep wells. Mechanisms of casing failure active in the study area include electrochemical and bacterial processes. Continued development of both shallow and deep groundwater resources, with steel cased wells constructed without annular grout, will eventually result in further deterioration of the freshwater resource.

The corrosion of iron or steel in aqueous solution occurs as a natural galvanic cell forms between two regions of differing electrical potential. This may be caused by nonuniformities in metal stress prevalent in driven casing, the joining of dissimilar metals, differences in temperature, or variations in flow rates. The electrolytic cell consists of an anodic area, where iron dissociates, and a cationic area, where atomic hydrogen is generated as follows:

Anode reaction

$$4Fe \text{ --- } 4Fe^{++} + 8e^{-} \quad (1)$$

Dissociation of water

$$8H_2O \text{ --- } 8H^{+} + 8OH^{-} \quad (2)$$

Cathode reaction

$$8H^{+} + 8e^{-} \text{ --- } 8H^{o} \quad (3)$$

The dissociation of iron at the anode results in pitting and the concentration of hydrogen at the cathode polarizes the area, protecting it from corrosion. In the absence of oxygen the product of this reaction is ferrous hydroxide, a black insoluble deposit found inside the casing of flowing wells throughout Lee County.

The chemistry of different groundwaters tends to accelerate or impede these reactions (Clark, 1980). Sodium reacts with excess hydroxyl ions to form sodium hydroxide which increases the pH at the cathode. This, in turn, increases the corrosion potential relative to the anode. Negative ions such as chloride and sulfate tend to migrate to the anode and prevent the formation of inhibiting films and thus increase corrosion rates. On the other hand, water containing dissolved calcium and bicarbonate ions react to form a protective calcium carbonate scale in the following reaction:

$$Ca^{++} + 2OH \text{ --- } Ca(OH)_2 \quad (4)$$

$$Ca(OH)_2 + HCO_3 \text{ --- } CaCO_3 + H_2O \quad (5)$$

Thick scale, while protecting casings from corrosion, often results in reduced casing diameters and decreased yield. Calcium carbonate scale, often over two inches thick, has been observed locally but not uniformly throughout Lee County.

All of these dissolved ions are present in the groundwater of Lee County; however, it is the relative concentrations of these various constituents which cause water to form protective scale or to be corrosive. Observations suggest that the corrosive character of waters in the study area vary both between different aquifers and within the same unit. Two methods used to assess the corrosive nature of groundwater are the saturation index (I_L) and the stability index (I_R). The saturation index originally proposed by Langelier (1936) is based on the relationship of the waters actual pH to a theoretical pH value assuming saturation with calcium carbonate. The saturated pH value (pHs) is calculated from the relation:

$$pHs = C + pCa + pALK \quad (6)$$

Where,

C is the total dissolved solids constant corrected for temp. in degrees centigrade.

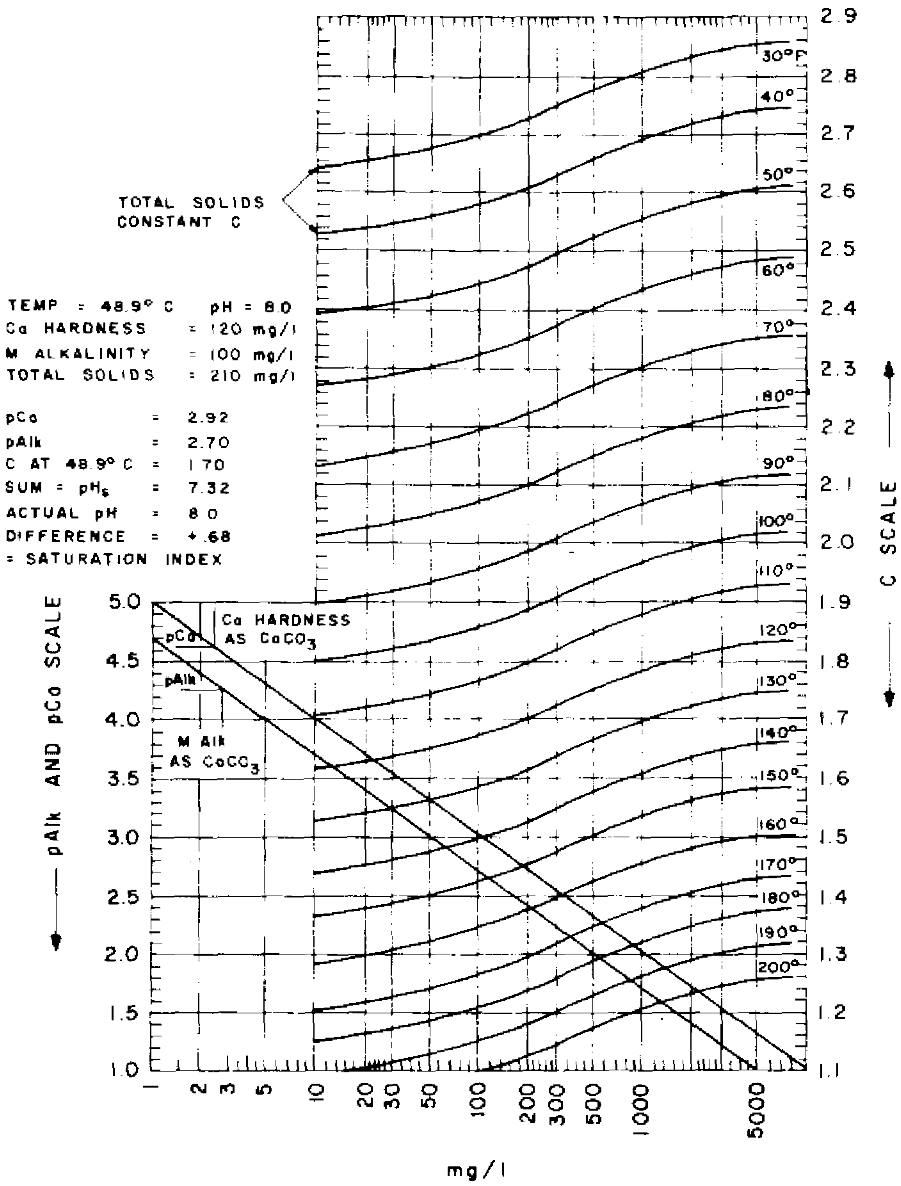
pCa is the negative log of the calcium concentration expressed as mg/l.

pALK is the negative log of the bicarbonate alkalinity expressed as mg/l.

Calculations can be made by inserting the appropriate water quality data in the chart shown on Figure 3. From this, the saturation index (I_L) equals the difference between the actual pH of the water (pH_a) and the theoretical saturated pH (pHs):

$$I_L = pH_a - pH_s \quad (7)$$

When the saturation index is a negative number the water is generally corrosive (Clark, 1980); protective scale will form if I_L is greater than zero.



F°		C°
30	=	-1.1
40	=	4.4
50	=	10.0
60	=	15.6
70	=	21.1
80	=	26.7
90	=	32.2
100	=	37.8
110	=	43.3
120	=	48.9
130	=	54.4
140	=	60.0
150	=	65.5
160	=	71.1
170	=	76.7
180	=	82.2
190	=	87.7
200	=	93.3

TO DETERMINE:

pCa: LOCATE mg/l VALUE FOR Ca (AS $CaCO_3$) ON THE mg/l SCALE. PROCEED VERTICALLY TO THE RIGHT DIAGONAL LINE, THEN ACROSS TO THE pCa SCALE.

pAlk: LOCATE mg/l VALUE FOR "M" ALKALINITY AS ($CaCO_3$) ON THE mg/l SCALE. PROCEED VERTICALLY TO THE LEFT DIAGONAL LINE, THEN ACROSS TO THE pAlk SCALE.

TOTAL SOLIDS: LOCATE mg/l VALUE FOR TOTAL SOLIDS ON THE mg/l SCALE. PROCEED VERTICALLY TO THE APPROPRIATE TEMPERATURE LINE, THEN ACROSS TO THE "C" SCALE.

Figure No. 3 NOMOGRAPH FOR CALCULATING LANGELIER INDEX I_L

The stability index (I_R) proposed by Ryzner (1944) is considered to be a more quantitative indicator of the corrosive nature of water. It is expressed by the equation.

$$I_R = 2_pH_s - pH \quad (8)$$

Experimental data indicate that calcium scale begins to form between index values of 6.0 to 6.5 and becomes increasingly heavy as the index decreases. Corrosion increases rapidly for values over 7.0.

Saturation and solubility indices for random water samples taken from different aquifers in Lee County are summarized in Table 2. Data indicate that water from the Floridan Aquifer System has a potential for scale formation while waters from shallower aquifers are more corrosive. This suggests that while the casing may be protected by heavy calcium scale frequently observed inside the casing, the process of corrosion is actively occurring along the outside wall of the casing. This explains why casing failures (observed by geophysical methods) occur adjacent to shallow producing zones despite thick accumulation of protective scale. While the values measured show trends toward corrosion and scale formation, it should be noted that the range of the corrosion values shown are considered mild to moderate. At such rates a casing life expectancy of 20 to 25 years is to be expected.

In addition to the chemical breakdown of casing, sulfur reducing bacteria are suspected to be present in deep wells throughout the study area. Sulfate reducing bacteria increase corrosion by utilizing free hydrogen ions, which polarize the cathode area of a galvanic cell to produce hydrogen sulfide in the reaction:

$$SO_4^{=} + 8H^+ \_\_\_\_ S^{=} + 4H_2O \quad (9)$$

$$S^{=} + 2H^+ \_\_\_\_ H_2S \quad (10)$$

As a result of the loss of hydrogen at the cathode, the errosion of iron at the anode is accelerated (Smith, 1982). Desulfomaculatum are strictly an

FLORIDAN AQUIFER SYSTEM			MID-HAWTHORN AQUIFER			SANDSTONE AQUIFER			SURFICIAL AQUIFER SYSTEM		
Well #[1]	Langelier[2]	Ryznar[3]	Well #	Langelier	Ryznar	Well #	Langelier	Ryznar	Well #	Langelier	Ryznar
WA-67	.91	5.87	L-702	.64	6.72	L-1418	.28	6.64	L-730	-.05	7.40
WA-118	1.43	5.60	L-1115	.60	6.80	L-1853	.07	7.07	L-739	.22	6.86
WA-123	1.05	5.09	L-1117	.77	6.36	L-1908	.20	6.90	L-1831	.10	7.00
WA-134	1.09	5.41	L-1973	.56	6.68	L-1974	.40	6.90	L-1982	-.15	7.70
WA-238	.72	6.30	L-2244	.30	7.30	L-1996	.12	6.88	L-1995	-.27	7.44
WA-316	.96	5.93	L-2641	.82	6.56	L-2192	00	7.10	L-2095	-.46	7.72
Sample Average	1.02	5.70		.62	6.74		.18	6.92		-.10	7.35

[1]WA: SFWMD Monitor Well
L: USGS Monitor Well

[2]Saturation Index I_L

[3]Stability Index I_R

TABLE 2. CORROSION INDICES (I_L and I_R) FROM REPRESENTATIVE SAMPLES TAKEN FROM LEE COUNTY AQUIFERS

anaerobic bacteria which thrive in deep wells of moderate salinity. Requiring a reducing environment prevalent in deep wells, these bacteria frequently exist in lobate encrustations or "tubercules" within the casing (Lewis, 1965). Redox potentials for flowing wells, with observed tubercule growth, range from -20 to -80 mV. The presence of H_2S, an indicator for the presence of Desulfomaculatum, in these same wells consistently exceeded the upper measuring limit of 5 mg/l. Corrosion is most intense at these tubercules and casing failures have been observed adjacent to tubercules in casing samples taken in Lee County.

Upward Saline Migration

The mechanisms influencing the upward movement of saline water active in Lee County have been postulated by several authors including: Sproul; Boggess and Woodward (1972); Boggess (1973); and Boggess, Missimer and O'Donnell (1977). Both faulting and well construction have been discussed. A review of their results is given below.

Evidence of faulting in Lee County was originally presented by Tanner (1965) in his theory on the origin of the Gulf of Mexico. He proposed two possible first-order shear planes associated with the theoretical plate movement bearing between N 30^{O}E to N 50^{O}E and N 70^{O}W to N 90^{O}W. Tanner theorized the offset in the Lee County coastline, bearing approximately N 50^{O}E, was caused by a fault active in the last 10,000 years. Additional evidence was presented by Sproul (1972) who described several faults in the McGregor Isles area as being responsible for temperature and water chemistry anomalies. These faults, identified by offset geophysical marker beds, are oriented approximately parallel to the N 70^{O}W bearing described by Tanner. Similar offset beds have been identified in Estero where wells of high salinity were logged for plugging. Correlation of marker beds within the lower Hawthorn/Tampa producing zone, identified from gamma and electric logs, are shown on Figure 4. It is not clear whether the offset is caused by folding or faulting; however, the apparent dips exceeding four degrees in less than 500 feet strongly suggest faulting. The orientation of the structural axes are within a few degrees of N 70^{o}W. The magnitude of the offset between wells on either side of an axis increases with depth through the Hawthorn Formation suggesting the origin of the structure occurred prior to Miocene sedimentation. The maximum offsets identified occur at the base of wells WA-102 and WA-103, and WA-105 and WA-107 with an apparent dip of $4^{o}30'$ and $6^{o}20'$, respectively. In 1976, Missimer and Gardner used high resolution continuous seismic profiles to identify subsurface structure along the Caloosahatchee River. The equipment used provided penetration through the mid-Hawthorn aquifer and into the top of the lower Hawthorn Formation but no data were presented for pre-Miocene sediments. The profiles indicated the middle and upper Miocene strata were extensively folded but not faulted.

Both the geophysical data presented by Sproul, et. al. 1972 and geophysical data collected during this study indicate the maximum displacement of beds occur at depth. The magnitude of the displacement decreases rapidly in more recent strata. This trend is also demonstrated in seismic data and suggests that if faulting exists, it occurs at depth and does not extend through the lower Hawthorn confining zone. Although there may be saline exchange due to faulting within the Floridan Aquifer System, there is no evidence to suggest that faulting is responsible for the contamination of the shallow principal aquifers in Lee County.

The primary cause of upward saline migration into the shallow freshwater aquifers is attributed to early well construction practices combined with the lack of subsequent well maintenance. Field data collected by the SFWMD indicates that approximately 26% of the Floridan wells in Lee County are

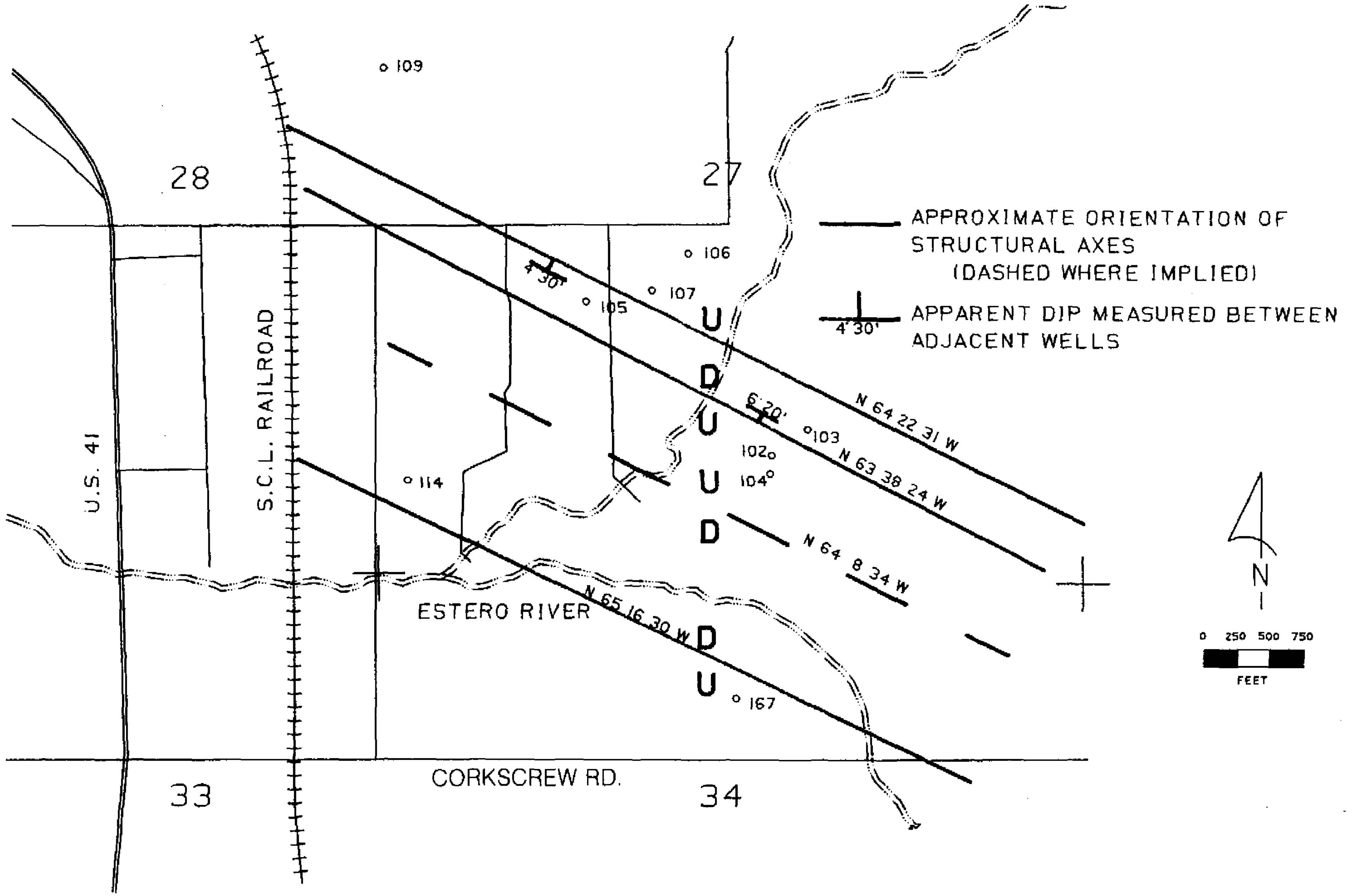


Figure No. 4 LOCATION AND ORIENTATION OF OFFSET BEDS IN THE LOWER MIOCENE; ESTERO, FLORIDA

uncontrolled and free flow continuously (205 wells surveyed). The average discharge from the uncontrolled wells was 86 gpm. In addition to surface discharge, internal flow resulting from differential head pressures between connected aquifer has been observed throughout the county. Sproul (1972) measured internal exchange from the Floridan into the mid-Hawthorn aquifer at 100 gpm in the McGregor Isles area. Similar internal flow rates have been measured in Lehigh Acres and the Buckingham area by SFWMD. A conservative estimate of the average rate of internal exchange for flowing wells in Lee County is five gallons per minute.

A generalized cross section depicting the paths of upward saline migration is shown on Figure 5. The potentiometric surface of the upper portion of the Floridan aquifer in Lee County ranges from +20 to +55 feet NGVD and exceeds the heads in all three principal freshwater aquifers throughout the county (Wedderburn et al. 1982). Differences in potentiometric heads ranging from 15 to 50 feet allow saline water to recharge the mid-Hawthorn aquifer directly through uncased portions of the well. Contamination of the Sandstone aquifer occurs by direct exchange in short cased wells, or through corrosion holes. The Surficial aquifer receives recharge directly from surface discharge.

An estimate of the total discharge into freshwater aquifers from Floridan wells in Lee County was presented by Healy in 1978. Using the figure of 3,000 flowing wells presented by Sproul (1972), Healy estimated a daily discharge of 90 mgd from both surface discharge and internal flow.

From 1979 to 1983 a total of 350 wells were surveyed by the SFWMD. Of these, 210 wells were located which were not included on the USGS deep well inventory (742 surveyed wells). From these data, a revised estimate of 1850 wells is proposed for the total number of deep wells in Lee County. This number is calculated from the rate of new finds combined with the original

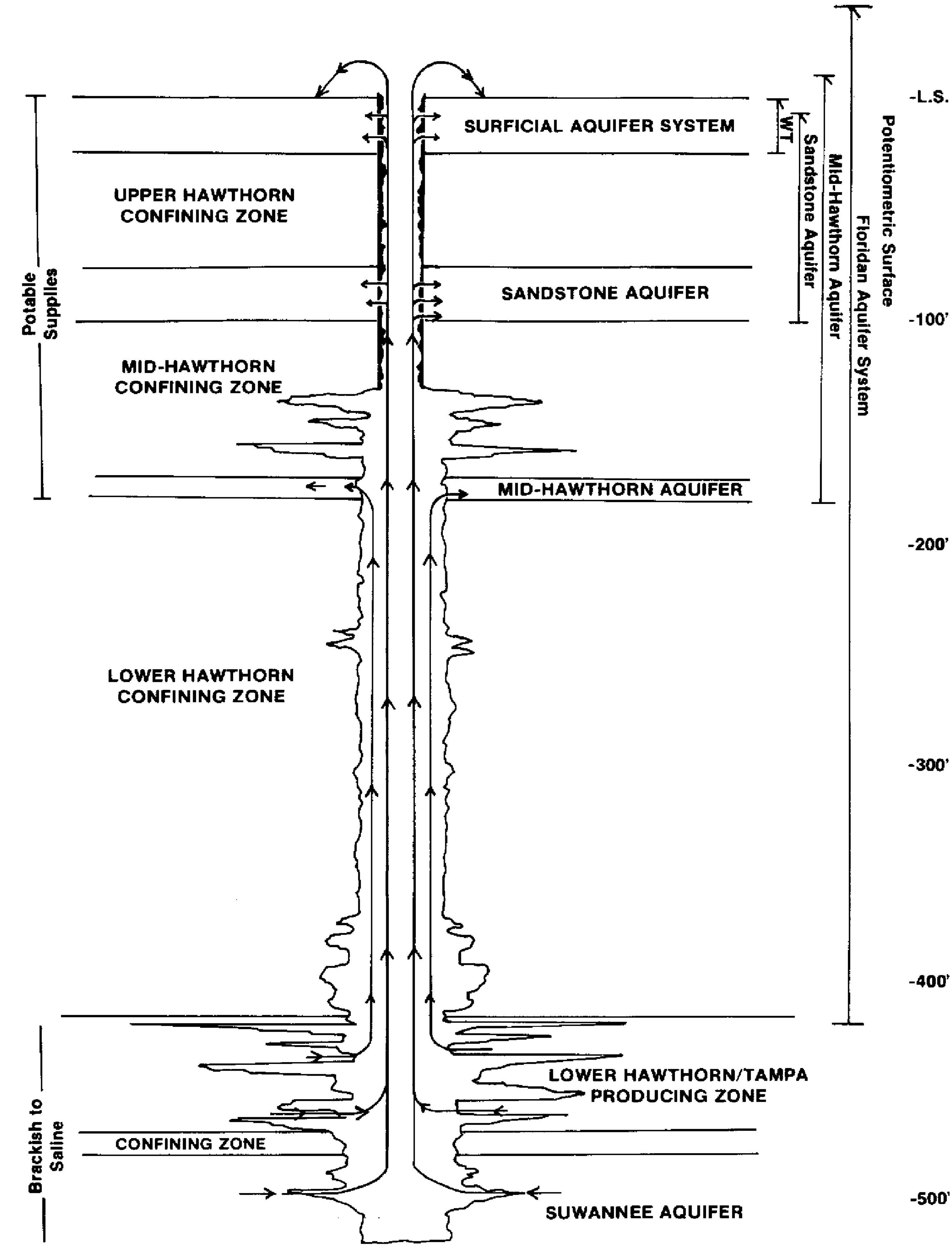


Figure No. 5 GENERALIZED CROSS SECTION DENOTING PATHS OF UPWARD SALINE MIGRATION

USGS inventory. Assuming 26 percent of these wells discharge continuously throughout the year at an average rate of 86 gpm, an estimated 59.6 mgd is calculated for surface discharge. By applying the average internal flow rate of 5 gpm to 91 percent of the wells (which are short cased to the mid-Hawthorn aquifer), the total flow loss for Lee County prior to any plugging activities was approximately 81 mgd.

The effect of continual discharge is reflected by the steady lowering of the potentiometric surface of the Floridan aquifer where declines of over ten feet have been reported between 1944 and 1973 (Boggess, 1974). The region of greatest decline occurs along the Caloosahatchee River where the majority of deep wells are concentrated. The result of this decline is often reflected by deterioration in water quality within the Floridan Aquifer System. This is exemplified in well WA-131 (L-541) located in the Iona District. The chloride concentration for this well rose from 1180 mg/l in 1950 to 5635 mg/l in 1981 (Wedderburn, et al, 1982). During this period the potentiometric head pressure dropped from 32 feet to 17 feet NGVD.

Downward Saline Migration

The steady decline in the potentiometric surface of the mid-Hawthorn aquifer, combined with steel cased wells located within tidal influence, provide the mechanism for downward saline migration in Cape Coral. Cape Coral, located in west central Lee County, was developed in the early 1960's. The area was originally low lying and frequently flooded throughout the year. In order to alleviate the problem of flooding and to provide residents with boating access to the Gulf of Mexico, a complex network of canals, which discharged into the saline waters of the lower Caloosahatchee River, was established throughout the development. Early residences were provided with a two-inch galvanized steel well drilled into the mid-Hawthorn aquifer to provide potable water and lawn irrigation. These wells were frequently located within 100 feet of a canal. The casings, driven with cable tool rigs, were not grouted in place and after being exposed to a fluctuating saline water table were rapidly corroded.

In the mid 1970's several municipal wellfields were developed in the mid-Hawthorn aquifer. By 1979, the potentiometric surface of the mid-Hawthorn aquifer in southern Cape Coral had dropped to over 20 feet below sea level (Wedderburn et al., 1982). As a result, the elevation of the saline water table in the vicinity of the canals exceeded that of the mid-Hawthorn and downward recharge occurred through corrosion failures in the casing (Figure 6). Several case histories are outlined by Boggess, et al. (1977).

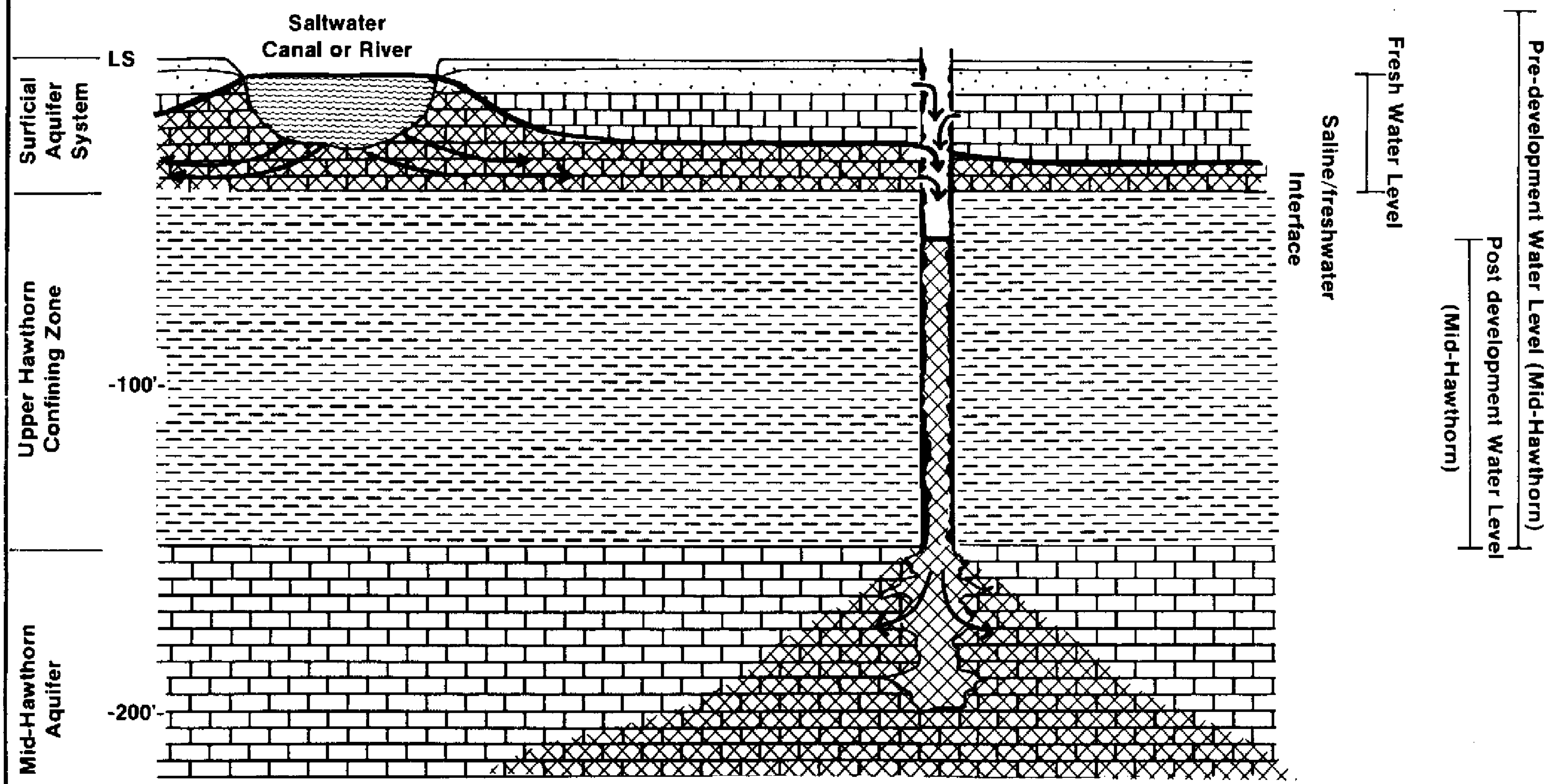


Figure No. 6 GENERALIZED CROSS SECTION DENOTING BRACKISH WATER RECHARGE OF THE MID-HAWTHORN AQUIFER.

GEOPHYSICAL APPLICATIONS TO WELL PLUGGING

In order to properly plug a well open to several aquifers, it is necessary to locate each producing zone, identify the water quality, and assess the degree of confinement between zones. To plug a well economically, fracture zones and washouts must be identified and isolated. Borehole geophysical surveys provide both site specific data for each well to be plugged and regional hydrostratigraphic information useful for the future development of the resource. The District operates a Gearhart-Owens model 3200 downhole logging system solely for well abandonment purposes. This four channel system is capable of data capture in both digital and analog format. Digital data is processed through the District's Well Log Analysis System. This system assimilates digital data and allows for a number of modifications including adjusting for common depth point, cross plotting, corrections for variations in temperature and borehole diameter, and scale changes. Data can be retrieved and displayed in a variety of formats. The surveys which constitute a suite of logs for well abandonment purposes are shown on Figure 7 and include natural gamma, flowmeter, caliper, 16 and 64 inch normal resistivity, spontaneous potential, casing collar locator, temperature gradient, differential temperature, fluid resistivity, and point sampler.

All aquifer systems in Lee County can be approximated by characteristic gamma activity associated with each unit. The Surficial Aquifer System and the Sandstone aquifer are usually cased off and are therefore identified solely by the increased gamma activity which occurs at the base of the Surficial System and throughout much of the Sandstone aquifer. The top of the mid-Hawthorn aquifer occurs beneath a high gamma emitting phosphatic regional disconformity (Missimer, 1978). The Lower Hawthorn/Tampa Producing Zone is identified on gamma logs by an attenuation of activity which occurs at the base of the Lower Hawthorn Confining Zone. The top of the Suwannee aquifer is identified by its virtual lack of gamma emitting minerals.

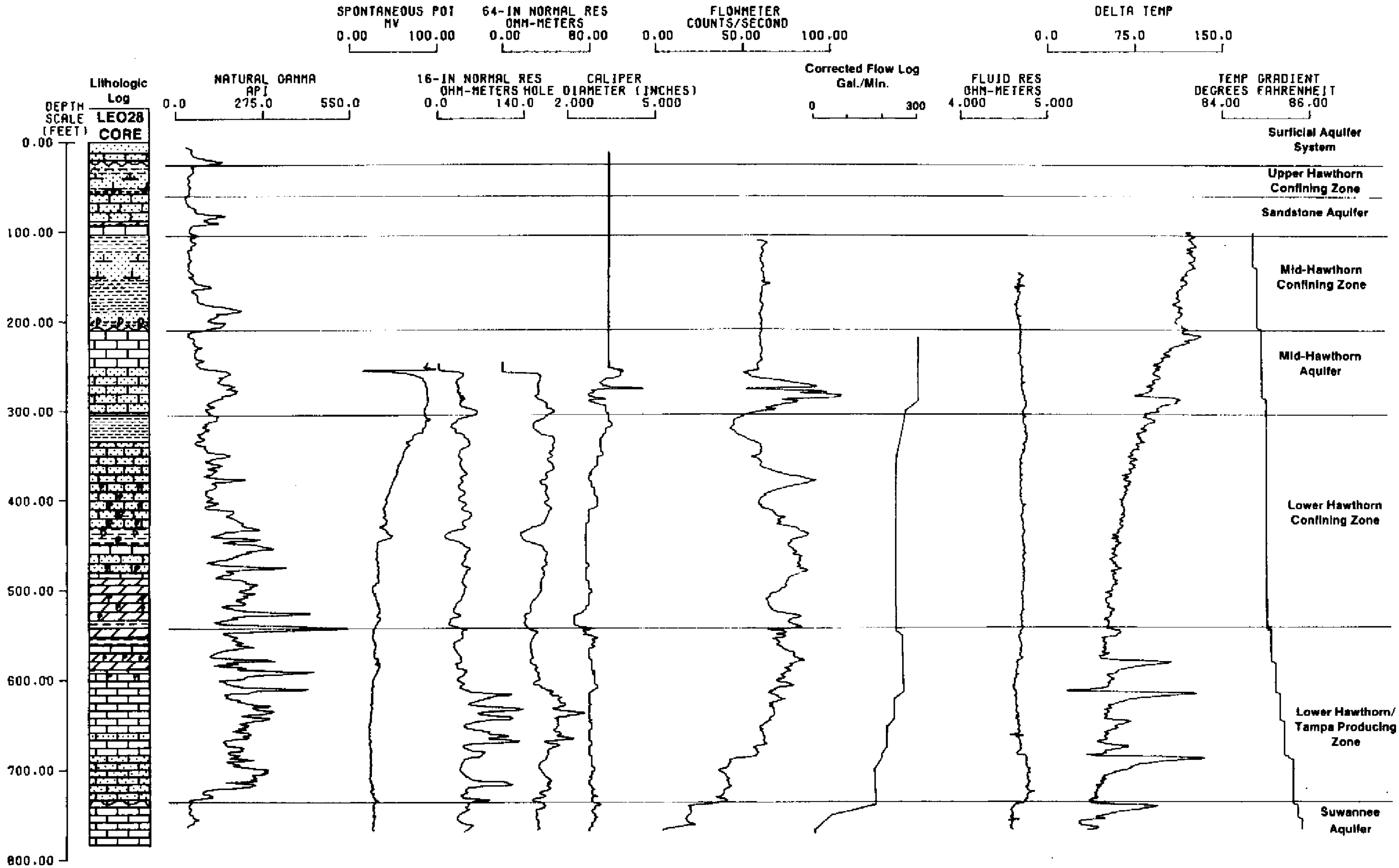


Figure No. 7 CORRELATION OF GEOPHYSICAL DATA FOR WELL LEO-28

The resistivity and spontaneous potential logs provide lithologic information necessary for the design of bridging plugs by identifying clayey confining zones and competent limestone/dolomite units. Although the dolo-silt confining zones contain only small percentages of mineralogic clay in Lee County, often there are enough clay minerals present to cause polarization of chloride and sodium ions about the confining bed. Cations move through the confining zone while the chloride ions concentrate at the limestone/dolo-silt interface resulting in a potential that can be identified on SP logs. Tight limestones and dolomites are identified by high resistivity values on both the long and short normal logs. Individual producing zones within the Floridan Aquifer System can also be located on resistivity logs where the flow of magnesium rich waters have resulted in the genesis of secondary dolomite in solution vugs.

Individual producing zones within the Floridan System are identified by anomalies in the geothermal gradient measured on temperature logs. Calculated yields from these zones are determined with a calibrated flowmeter lowered to an area of consistent diameter above and below each producing zone identified from the temperature logs. The yield (Y) in gallons per minute, is calculated from the relation:

$$Y = 0.014 \ K \ vr^2 \qquad (11)$$

Where,

v = the measured flow from the impeller tool (counts per second (cps))

r = the radius of the tested interval (inches)

K = the flowmeter constant determined empirically (in/min x 1/CPS)

The constant 0.014 is the product of π and the number of gallons in a cubic inch. The flowmeter constant (K) describes the tool's response to different velocities for a given blade and basket assembly. K is the ratio between the measured flow velocity in inches per minute and the response of the flowmeter in counts per second. The value for K is usually calculated in the casing of a well prior to logging.

Point sample water quality data taken above and below each producing zone is corrected for the effect of mixing by the mass balance equation (Brown, et. al., 1981):

$$[X]_{zone} = \frac{Q_a\ [X]_a - Q_b\ [X]_b}{(Q_a - Q_b)}$$

Where,

$[X]_{zone}$ = the corrected concentration of the chemical parameter in question

$Q_a\ [X]_a$ = the product of the borehole flow and concentration of the chemical parameter measured above the producing zone

$Q_b\ [X]_b$ = the product of the borehole flow and concentration of the chemical parameter measured below the producing zone

These data are particularly useful in determining plugging and rehabilitation designs where producing zones of differing water quality must be identified and isolated.

Borehole geophysical methods are also used to identify interaquifer exchange within wells. Exchange between the Floridan and mid-Hawthorn aquifer is measured directly by flowmeter. A calibrated flowmeter is lowered to an interval of uniform diameter within the confining zone between the units and the well is shut in at the surface. The exchange rate, excluding frictional loss, is equal to the flow rate calculated from equation 11.

Flow losses occurring into the Sandstone aquifer through corrosion holes in casings have not been quantitatively measured by flowmeters in this program but they are frequently identified by other methods. While the caliper is sometimes useful in locating large breaks in the casing, the mechanics of the tool and casing encrustation prevent the identification of small holes. The casing collar locator, which indicates variations in a self-generated magnetic flux, is useful in identifying variations in casing thickness caused by corrosion. In wells which have been allowed to flow for some time, the differential temperature survey (capable of measuring changes in temperature of 1/100 of a degree Farenheit) locates cooler water entering the well from the shallow aquifer via the Venturi effect.

A frequent problem encountered during logging was having a probe stuck in the well. This problem often occurs in old wells drilled with cable tool rigs through alternating clay and limestone units. The drill bit wanders at density interfaces, clays squeeze in and reduce the borehold diameter, and the wells are seldom drilled normal to land surface. As a result, a probe run into a well will often drag along the bore wall with the cable constantly abrading any shelf or irregularity in the borehole. Eventually the cable cuts a narrow groove or keyhole which prevents the probe from being retrieved (Figure 8). Swabbing the well with a large diameter steel "dummy" probe helped reduce the problem but did not alleviate it. After several costly and unsuccessful attempts by local contractors to retrieve stuck equipment, an inexpensive and reliable method of "fishing" was devised by SFWMD. This technique involves the use of 2" PVC pipe equipped with flush treaded couplings which is carried in 10 foot sections on a support vehicle. When the probe is stuck, a grooved aluminum "fishing" head is fitted over the conductor cable. The fishing head is attached to the PVC pipe and is lowered to the probe. The fishing head pushes the cable out of the keyhole as the string of pipe is bounced, freeing the probe. The probe is then pulled into the fishing head and the string of pipe and probe removed. Because PVC has almost the same specific gravity as brackish water, a 400 foot string of pipe can be

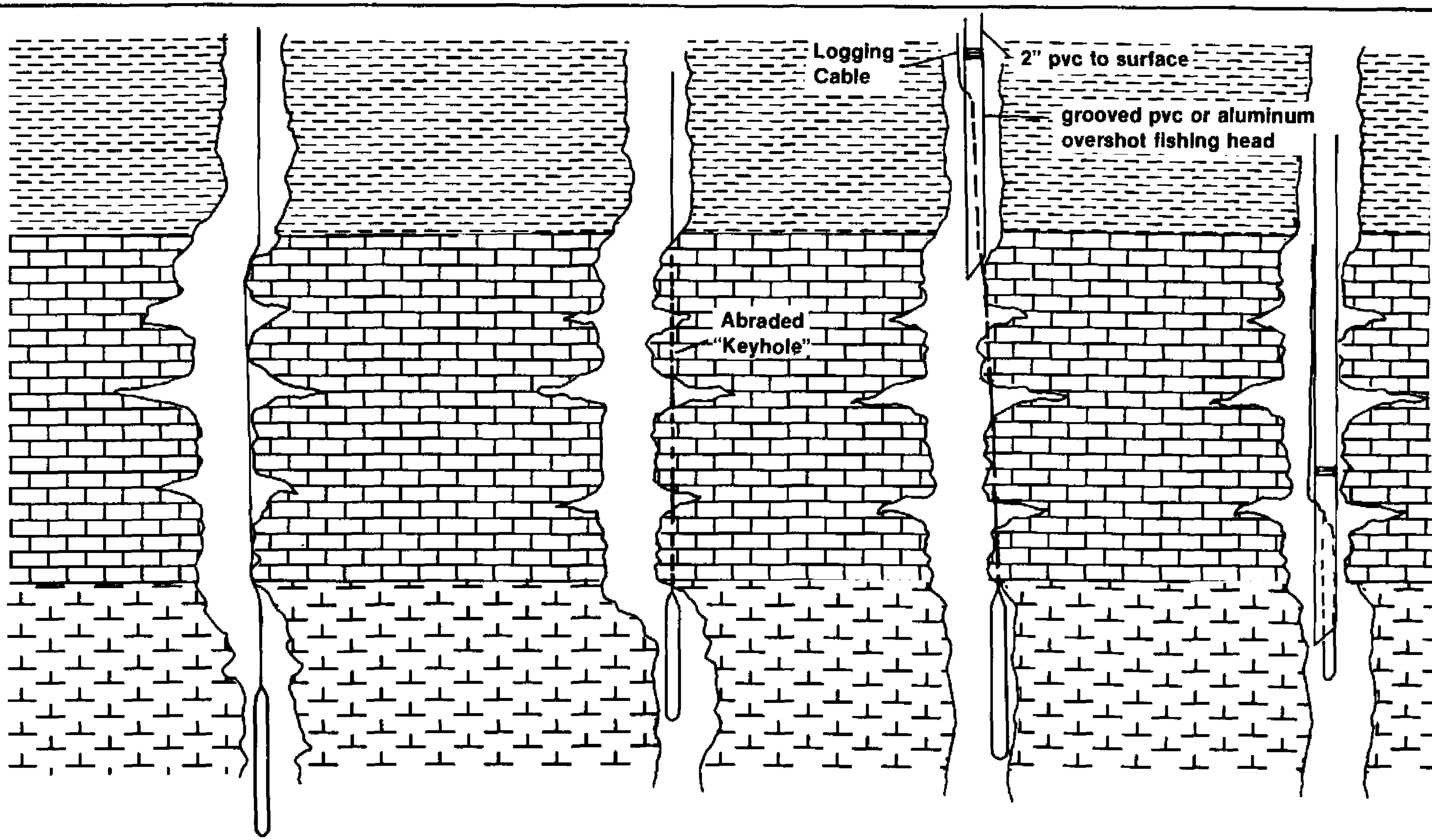


Figure No. 8 LOST PROBE RETRIEVAL METHOD UTILIZED BY SFWMD

easily handled by two men. The technique allows for recovery without cutting cable so logging can proceed after fishing without a loss for down time. To date (1983), this method has been used successfully 17 times, recovering over $26,000 of equipment (only four dummy probes have been irretrievably lost all inside encrusted casings where the fishing tool could not reach the probe). The PVC is also used to line wells past partial obstructions, which allows wells to be logged which were formerly considered blocked off.

METHODS OF WELL PLUGGING

To permanently plug a well open to several producing zones, it is necessary to isolate each zone by replacing the natural confining zones with a material of equal or superior confining properties. When dealing with a large number of wells this must be done in a cost effective manner. While methods of plugging flowing wells range from "stumping" (wedging a log into the casing below grade and burying the well) to dynamite, there are three basic methods generally recognized for effective well plugging. These methods, used by SFWMD, are: a) packer installation, b) backfilling, and c) stage grouting.

A packer, as used in plugging operations, refers to any permanent impermeable bridging device. While being the most precise method of isolating producing zones, packers are often cost-prohibitive for widescale use. A variety of more colorful alternatives have been devised by local contractors which include wooden posts, sacks of dried beans, or cow dung mixed with bentonite, all of which rely on hydraulic expansion of the material to form an impermeable seal. These methods, while posing obvious environmental hazards, are in themselves extremely unreliable short-term solutions. In contrast, the more elaborate mechanical well packers used by the oil and groundwater industry are cost-prohibitive. Investigations have produced two cost effective, environmentally sound packers. The first, the QWIP plug developed by SWFWMD, is an inexpensive cement inflatable packer. This device consists of PVC pipe covered with a coarse mesh burlap sock which is fabricated to a larger dimension than the borehole. The bottom four feet are constructed with strong impermeable vinyl fabric which confines the bottom of the plug (Figure 9). The length of the plug and volume and weight of cement needed to inflate it are based on the head pressure of the well. The packer is set adjacent to a competent confining zone with drill rod. Cement is pumped through the drill rod and into the plug through holes at the base of the PVC

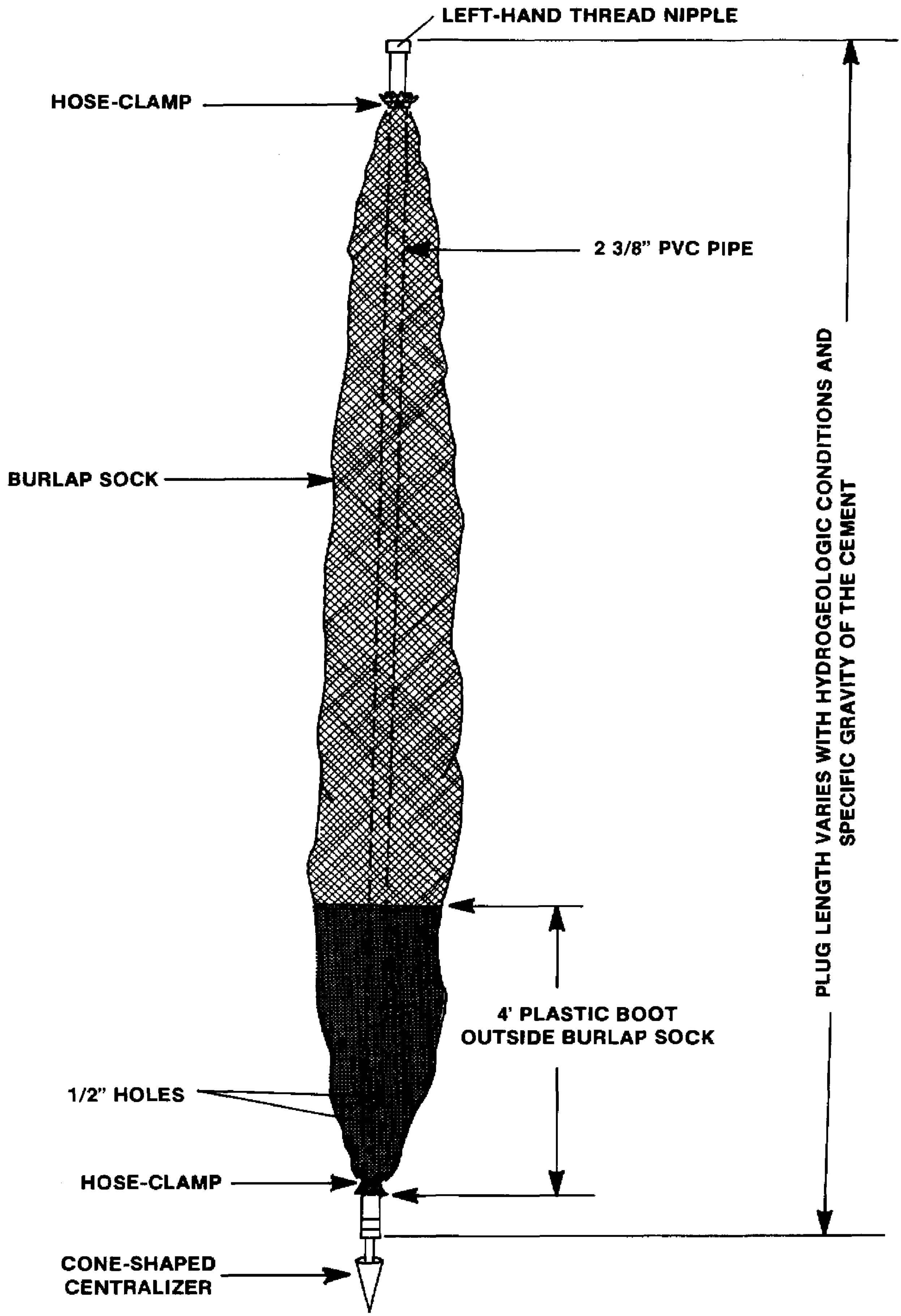


Figure No. 9 DIAGRAM OF SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT'S QWIP BRIDGING PLUG

core. Cement weeps through the burlap forming a positive seal to the bore wall. This device has been used extensively by SWFWMD and by the SJRWMD but has had limited use in Lee County.

The second device, a gravel-bentonite packer, consists of a burlap sack over a PVC pipe which is filled with fine gravel and dry granular bentonite. It is lowered to a confining zone and held in place for 20 to 30 minutes as the bentonite expands and conforms to the bore wall. The plug is then detached from the drill stem and cemented in place. The advantage of this type of packer is that the driller can set it without having to pump cement through a drill stem as with the QWIP plug. This device is widely used outside of Florida in both flowing and non-flowing wells; however, it has limited applications in saline wells as dissolved salts impede the hydraulic expansion of bentonite. Because of this, the gravel-bentonite packer is not applicable for most of Lee County's flowing wells.

Backfilling is used to fill voids, fractures, or washouts associated with most wells. Backfill can be used adjacent to producing zones, if possible, to prevent slurry loss, or in between cement stages within thick confining zones. The material most often used for backfill is clean crushed stone or sand treated with calcium hypochlorite to prevent biologic contamination. Emplacement of backfill is complicated by "bridging" in most wells, and to insure proper placement the fill must often be tamped in place with drill rod. There are obvious limitations on the use of backfill in flowing wells; however, once the flow is stopped with packers or stage grouting, backfill is an economic alternative to straight grout.

By incorporating site specific data provided by geophysical methods with potentiometric head pressures, conventional bottom to top grouting can be supplemented by stage grouting. Stage grouting utilizes the upward hydraulic force exerted by a flowing well to balance an unconfined specific volume of slurry of a given weight. This technique is used to isolate individual flow zones without the use of a packer. Because less cement is used (compared with conventional bottom to top continuous plugs) stage grouting is useful in reducing the volume of slurry lost to the formation caused by excessive weight.

There are two approximations used to calculate the amount of slurry needed for each stage in the Floridan Aquifer System; the minimum weight needed to compensate for the hydraulic head of a flow zone and the volume needed to overcome the difference in flow rates between the well and the slurry pumpage rate. The upward force P (in pounds) exerted by the producing zone is a function of head, measured from land surface, and the capacity of the well:

$$P = 8.3\,C\,(h_1 - h_2) \qquad (13)$$

Where,

C = capacity of the well casing (gal/ft)

h_1 = the potentiometric head (in feet) of the flowing well referenced from land surface

h_2 = the potentiometric head of the next overlying, uncased producing zone or aquifer with a potentiometric head below land surface

In Lee County, the h_2 term, referenced from land surface, applies primarily to those wells in which the mid-Hawthorn aquifer is not cased off. In those areas where the well is fully cased into the Floridan System, the h_2 value is zero. Approximation of h_2 values are obtained from regional potentiometric surface maps. Due to the magnitude of the physical variables and the degree of error in estimating h_2, corrections for specific gravity and temperature are not applicable. In deep wells which contain several independent producing zones within the Floridan Aquifer System, the value for P, calculated at land surface prior to plugging, is applied to each zone. While this assumption is not always accurate, field tests of wells with diameters up to eight inches indicate a significant tolerance for slurries with excessive weight. Using high viscosity slurries, slurry stages weighing over 20 times the calculated value of P have been successfully floated in wells. This is attributed to the degree of cohesion in high viscosity cement-bentonite slurries combined with the small diameter and roughness of the borehole. It is not known if this tolerance for excessive weight holds for wellbores greater than eight inches; however, existing data suggests that greater precision is required for large diameter wells.

The second approximation allows for the amount of slurry that will be diffused and held in suspension due to differential flow velocity when pumping first begins. Using 1¼ inch PVC tremie pipe it is difficult to exceed a pumping rate of 30 gpm when using a high viscosity slurry. In wells flowing several hundred gallons per minute the first portion of slurry is put in suspension and acts as a drill fluid coating the bore wall and weighing down the borehole fluid. The higher the velocity of the water in the borehole, the greater the pressure drop along the bore wall. This causes greater amounts of suspended slurry to migrate to the sides of the well. While unable to calculate the amount of slurry which stays in suspension or the point at which the well will stop flowing, an upper limit can be derived using the ratio between the formation discharge (Q_f) taken from a corrected flow log and the rate of slurry discharge (Q_s). This value is multiplied by the calculated value of P divided by the weight of the slurry W (in pounds per gallon) to yield the volume of the stage V (in gallons).

$$V = \frac{P}{W} \left(\frac{Q_f}{Q_s}\right) \tag{14}$$

The only remaining factor to be considered is the amount of slurry lost to the formation. This value, known as the Formation Loss Factor (F), is the ratio betwen the actual measured footage plugged (L_a) and the theoretical linear footage (L_t) which is based on the volume of slurry pumped and the capacity of the well.

$$F = 1 - \left(\frac{L_a}{L_t}\right) X\ 100\% \tag{15}$$

Shrinkage of the slurry while setting is negligible for high bentonite slurries which exhibit little shrinkage. Field data in Lee County for wells drilled with cable tool rigs indicate values for F range between 15 and 20 percent in the Floridan Aquifer System. The values for F decrease to 10 percent or less in the lower Hawthorn Confining Zone.

Once enough stages have been pumped to isolate each producing zone in the Floridan Aquifer System, the tremie pipe is removed and the contractor is paid to stand by while the slurry sets. After a slurry sample sets, the remainder of the well is backfilled and grouted to surface. It is not necessary for casings to be ripped or perforated prior to grouting, due to the lack of annular space inherent to cable tool drilling and due to the hydraulic expansion capabilities of the clayey confining materials.

The properties of the cement used to plug a well can be modified to fit specific needs by using various slurry additives. Three basic additives have been used in this program: bentonite, barite, and calcium chloride. Bentonite is used to seal the formation walls, decrease cement shrinkage, and to reduce the slurry weight. It is used in concentrations up to 15 percent to produce high viscosity slurries with weights below 13 pounds per gallon. It is used in smaller concentrations to reduce formation loss and to increase the per sack yield of straight cement (Table 3). In highly fractured formations, especially at depths over 800 feet, loss circulation materials such as Micatex® and Fibertex® are added to cement bentonite slurries to further reduce formation loss. Bentonite is also mixed with crushed stone or sand to fill washout voids or fractures. Fresh water must be used with bentonite since dissolved solids inhibit clay expansion and render the additive useless. When fresh water isn't available, salt tolerant muds containing attapulgite (Zeogel®) are used instead of bentonite to increase viscosity. Barite replaces bentonite to reduce formation loss in high pressure wells where slurry weights over 15 pounds per gallon are needed. Calcium chloride is used as an accelerator to reduce setting time. When used in concentrations between 3 to 5 percent it allows straight Portland Type A slurries to set in one hour or less. When used with formation water high in dissolved calcium chloride, flash setting can occur. This phenomenon has proven useful in preventing floating plugs from sinking to the bottom of the well.

A case study of well number WA-51 is presented as an example of the techniques described. WA-51 was drilled in the late 1950's for agricultural purposes and was geophysically logged in February 1980. It was 823 feet deep, contained 115 feet of six inch steel casing, and flowed at a measured rate of 310 gpm. Interpretation of geophysical data indicates the flow occurred from three major zones located at -720 to -740, -520 to -535, and -400 to -440 feet below land surface (LS). There was no flow below -720 feet. The top of the Suwannee aquifer was identified at -520 ft. L.S. and the top of the lower Hawthorn/Tampa producing zone occurred at -360 ft. L.S. The mid-Hawthorn aquifer was identified between -110 to -200 ft. L.S. and was not cased off. The average borehole diameter was seven and one-half inches.

Percent Bentonite	Water Requirements Gal/Sk	Water Requirements Ft^3/Sk	Slurry Weight lbs/Gal	Slurry Weight lbs/Ft^3	Slurry Volume Gal/Sk	Slurry Volume Ft^3/Sk	Setting Time >2000 (hrs)	Compressive Strength PSI at 80° F 12 hrs	24 hrs	72 hrs
0	5.2	0.70	15.6	117	8.8	1.18	2:14	580	1905	4125
2	6.5	0.87	14.7	110	10.2	1.36	2:25	455	1090	2840
4	7.8	1.04	14.1	105	11.6	1.55	2:26	220	750	1775
6	9.1	1.22	13.5	101	12.9	1.73	2:16	85	360	1170
8	10.4	1.39	13.1	98	14.4	1.92	2:31	50	265	720
10	11.8	1.48	12.7	95	15.7	2.10	*	*	*	*
12	13.0	1.64	12.3	92	17.1	2.29	*	*	*	*

Percent Bentonite	Setting Time 2% $CaCl_2$(hrs)	Setting Time 4% $CaCl_2$(hrs)	Compressive Strength PSI at 80°F 2% $CaCl_2$ 6 hrs	8 hrs	12 hrs	18 hrs	24 hrs	Compressive Strength PSI at 80°F 4% $CaCl_2$ 6 hrs	8 hrs	12 hrs	18 hrs	24 hrs
0	1:30	0:47	685	1230	1675	2520	3125	960	1490	2010	2800	3080
2	2:00	0:56	350	620	1150	1805	1820	535	730	1100	1610	2020
4	2:41	1:52	170	240	500	785	1085	265	335	355	865	1195

*no data presented

TABLE 3. SLURRY YIELDS AND WEIGHTS FOR PORTLAND TYPE A CEMENT/BENTONITE SLURRIES (FROM HALLIBURTON, 1975)

On August 24, 1983, WA-51 was plugged. Prior to plugging, the potentiometric head was measured at +16 ft. L.S. The potentiometric head for the mid-Hawthorn aquifer was approximately -10 ft. L.S. at this time. Using equation 13, the value for P was calculated as 320 lbs. Using a 13 lb/gal slurry and a Q_S value of 30 gpm, the value of V calculated from equation 14 was 235 gallons (rounded). The first stage, consisting of 650 gallons of slurry was pumped at a depth of -560 ft. L.S. This large volume of slurry was used to test the wells response to excessive slurry weights and to attempt to cement off the flow zone occurring at -535 ft. L.S. The slurry contained 4.4 percent bentonite to reduce formation loss, and 100 lbs. of calcium chloride which was added to the last 300 gallons of slurry (approximately five percent). After the stage was pumped, the tremie was removed and the well capped at land surface. The following day, the well was flowing at approximately 125 gpm and the top of the plug was tagged at -472 ft. L.S. Assuming an average borehole capacity of 2.3 gal/ft, the theoretical length of the plug was calculated as 283 feet.

It is apparent that the excessive weight of this stage caused the plug to sink. However, the location of the top of the plug at -472 ft. L.S. indicates that the plug did not sink to the bottom of the well. The base of the plug was located at approximately -720 ft. which corresponds to the top of the deepest producing zone. This assumption is based on the fact that there is no upward force to balance the weight of the slurry below -720 ft. L.S. If slurry were able to pass below 720, the entire plug would sink to the bottom of the well. The formation loss factor F, assuming the base of the plug at -720 ft., was calculated as 14 percent for this stage.

A second stage, consisting of 56 bags of cement, 350 pounds of bentonite, and 200 lbs of calcium chloride was pumped from a depth of -320 ft. L.S. The top of the second stage was located the next day at -102 ft. L.S. The base of the plug was located at approximately -400 ft. L.S. The theoretical length of the plug was 335 feet and the actual length is 298 feet. Therefore, the formation loss factor F for the second stage was 11 percent. The remainder of the casing was cemented to land surface.

A total of 1,585 gallons of slurry, consisting of 116 bags of cement, 650 ponds of bentonite, and 400 pounds of calcium chloride were used to plug WA-51. By applying the average value for F of 12.5 percent to the calculated capacity of the borehole prior to plugging, the total volume of slurry needed to fill the well bottom to top would have been approximately 2000 gallons. The difference between the volume needed to fill the well and the volume of slurry actually pumped is 415 gallons which is equivalent to 180 linear feet of borehole. Based on the assumed location at the bottom of the two plugs, a total of 172 feet of borehole was not cemented, which indicates the base of the plugs are within a few feet of the -720 and -400 foot depths proposed.

In both the first and second stage, the excessive weight of slurry caused the plugs to sink to the top of a major flow zone. These data, along with similar test results, suggest a tolerance for larger slurry stages than those calculated from equations 13 and 14. While extra slurry weight may provide insurance against having a stage washout, excessive volumes are not needed to effectively isolate a producing zone and, in some cases, may be a waste of materials.

Between 1979 and the end of the 1982-83 fiscal year, a total of 268 wells had been plugged under the SFWMD - Lee County deep well programs. A total of 27,125 bags of cement and 1,900 bags of bentonite were used to plug 146,822 linear feet of borehole. The average flowing well plugged was 544 feet deep and was constructed with 130 feet of six inch steel casing, at a cost of \$1,825.03. A total of 542 wells were plugged under the SFWMD - Cape Coral shallow well co-op. The average Cape Coral well was 120 feet deep, constructed with two inch steel casing, and required 7.3 bags of cement to plug. The average cost per well was $176.06. A detailed summary of the costs and materials used in these programs is included in Appendix III.

WELL REHABILITATION

In many cases a well can be rehabilitated to yield better quality water at a lower cost than drilling a new well. Rehabilitation involves eliminating inter-aquifer connection afforded by the original construction while providing adequate quantity and water quality to suit the needs of the user. In order to prevent leakage through the old steel casing, all rehabilitation designs require the emplacement of a PVC liner which is cemented in place from land surface to the top of the aquifer to be developed. Site specific information including corrected flow log, fluid resistivity, and point sampler data are necessary to assess the feasibility of rehabilitation. While there are no funds available for rehabilitation through this program at this time, a brief discussion on rehabilitation may be useful to well owners or contractors. The most common method, known as partial plugging, involves cementing off the deep saline zones of a well while preserving shallow freshwater zones.

If geophysical data indicates a marked decrease in water quality with depth in the Floridan Aquifer System, it is possible to selectively cement off the deeper saline producing zones while preserving the better quality flow zones. This technique is applied to agricultural properties where free flowing wells are preferred, and has been widely used in St. Johns County by the St. Johns River Water Management District's plugging program (Munch, 1978). Flowmeter logs and point sample water quality data should be considered to determine the water quality and yield of the well after rehabilitation. An example of this method of rehabilitation is shown for well WA-85 on Figure 10. Fluid resistivity data identified saline water entering the borehole near the bottom of the well. A flowmeter survey was run and point sample data were collected above and below the six producing zones identified. Water quality data were corrected for the effects of mixing. At the time of testing (July 1980), the chloride concentration at the well head

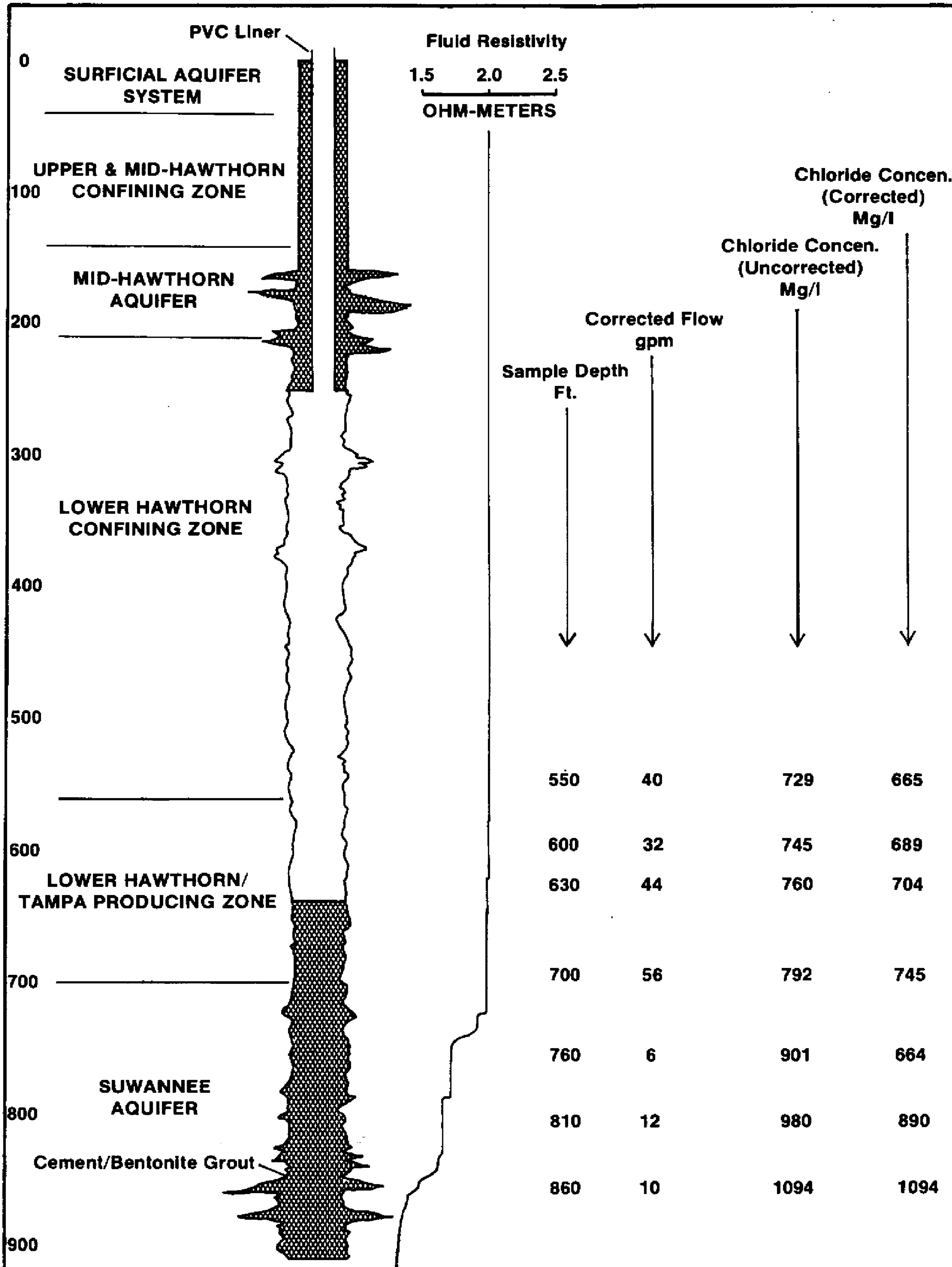


Figure No. 10 REHABILITATION DESIGNS FOR WELL WA-85 was 771 mg/l. The owner installed the PVC liner as shown, but didn't cement off the base of the well. By August, 1983, the chloride level measured at the well head had increased to over 1000 mg/l indicating further increases in salinity from the deeper producing zones. By plugging the bottom 250 feet of the well, the flow will be cut in half and the chloride level will drop to approximately 700 mg/l.

A second application of partial plugging pertains to wells in which the mid-Hawthorn aquifer is not cased off. In these wells, the entire Floridan Aquifer System is cemented off, leaving the mid-Hawthorn aquifer available for development. The major advantage to this method is the improvement in water quality; however, the mid-Hawthorn aquifer does not free flow in much of Lee County and, in many cases, the rehabilitated well will require a pump.

An example of this type of partial plugging is shown on Figure 11. Well WA-181 was 444 feet deep and contained 110 feet of four inch steel casing which was set in a limestone unit (twelve mile slough limestone) as determined from the 16" and 64" normal resistivity logs. A flowmeter and temperature survey determined that the entire flow (260 gpm) was from a single producing zone at the base of the well. The well was valved off and an internal flow rate of 55 gpm was measured between the lower Hawthorn/Tampa producing zone and shallow artesian aquifers. As there is no central water and sewer system in this area, the owner of WA-181 was notified his well was contaminating a potable aquifer system. The owner requested partial plugging to maintain a supply of water to his cattle and agreed to emplace a PVC liner at his expense. At the time of plugging (June 30, 1983) the chloride concentration at the well head was 1044 mg/l. The well was cemented back to -160 ft L.S. and was allowed to set for three days prior to development. By October 26, 1983, the chloride concentration had dropped to 757 mg/l. The well flows freely at a rate of 15 gpm.

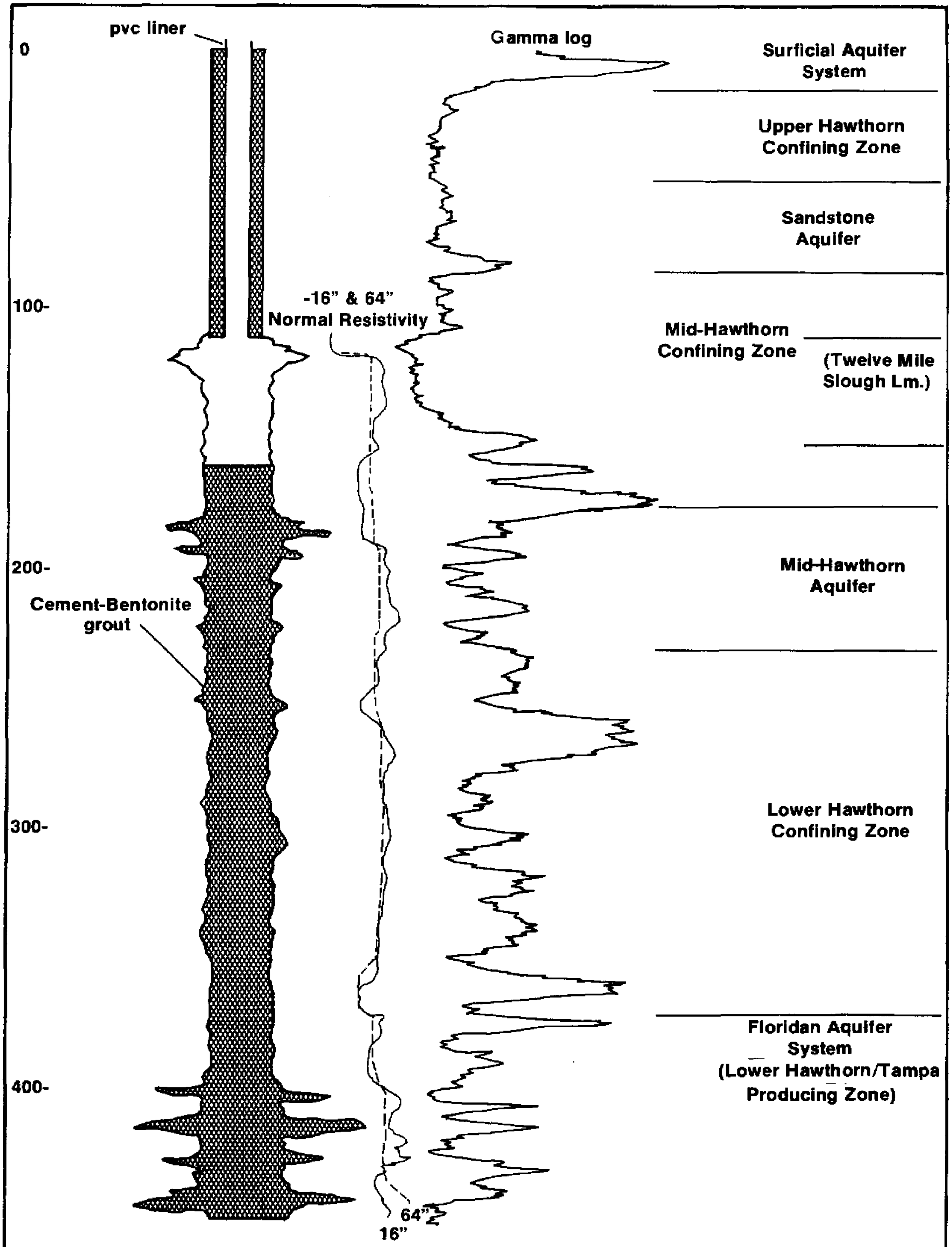


Figure No. 11 REHABILITATION DESIGNS FOR WELL WA- 181

Water quality recovery for the two methods of partial plugging described vary in both magnitude and time. For wells which are back plugged to the base of the mid-Hawthorn aquifer, the time required for water quality parameters to reach background levels is dependent upon the extent of intrusion and to the degree in which the rehabilitated well is used after partial plugging. In general, a rapid drop in salinity is experienced within months of rehabilitation; however, complete recovery takes several years. In Lee County, background chloride levels for the mid-Hawthorn aquifer are generally below 500 mg/l west of the Caloosahatchee River and below 250 mg/l east of the Caloosahatchee. In contrast, recovery is almost immediate for wells which are partially plugged to tap a single zone within the Floridan Aquifer System. In such a case, chlorides from well WA-136 dropped from 1120 mg/l to 840 mg/l in just one day. Figure 12 indicates similar rapid recovery rates occur in the Florida Aquifer System in St. Johns County. Well SJ-147 was partially plugged in November 1976 with an initial chloride concentration of 2800 mg/l. Days after plugging, the chlorides had dropped to 1950 mg/l, and by December 1976 had dropped to 740 mg/l. This rapid rate of water quality recovery is attributed to the relative equality of the potentiometric levels for each producing zone in the Floridan Aquifer System. The lack of a hydraulic gradient between producing zones limits the extent of interaquifer exchange. While isolating a single zone in the Florida Aquifer System may yield rapid water quality improvements, minimum chloride levels for the Floridan in Lee County are rarely less than 600 mg/l.

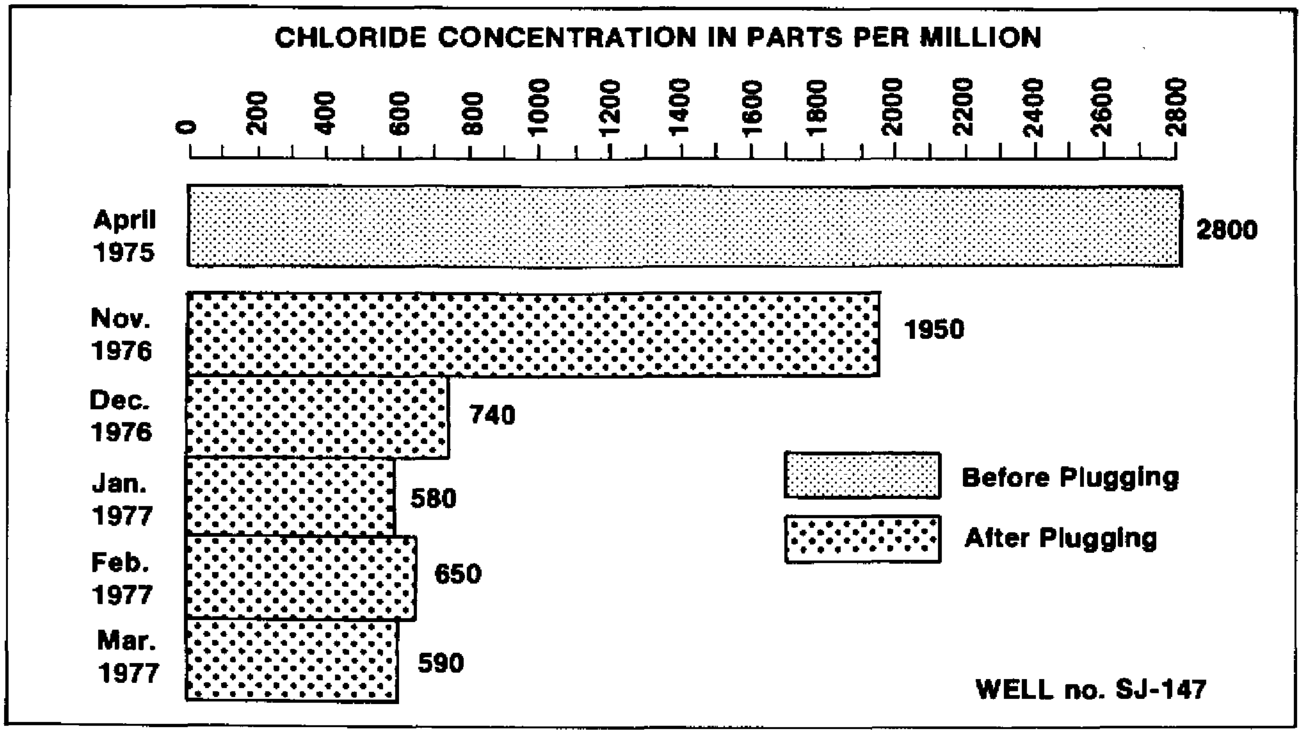


Figure No. 12 WATER QUALITY DATA FROM A PARTIALLY PLUGGED WELL IN THE FLORIDAN AQUIFER SYSTEM IN ST. JOHNS COUNTY, FLA. (FROM MUNCH, 1978)

EFFECTS OF WELL PLUGGING ON GROUNDWATER SYSTEMS

The rate at which the water quality in an aquifer recovers from point source contamination depends primarily on the extent of the contamination, ambient ground water velocities, and the hydrodynamic dispersion of the contaminant through the invaded aquifer. Additional parameters considered in solute transport problems such as distribution coefficients, ion exchange capacities, decay constants, branching ratios and coupling ratios between pores, and fractures pertain to site specific problems and are not considered here. In Lee County where saline wells have been leaking or free flowing for decades, the systems are assumed to have reached steady state and the period of contamination is considered to be infinite.

The extent of a saline plume generated by a single well is related to the rate of contaminant discharge, the salinity of the outflow, and the hydraulic properties of the invaded aquifer. Where topsoils are permeable, virtually all water which discharges on land surface enters the water table aquifer with the rate of discharge being directly related to the areal extent of the contamination. In Lee County, where many of the flowing wells occur on agricultural properties, much of the flow is diverted through ditch irrigation systems. In these areas, saline plumes are influenced by surface features as well as by the hydraulic properties of the aquifer. The rate of internal flow into the shallow artesian aquifers is dependent on the differential pressure between aquifers and the permeability of the invaded zone. The potentiometric surface of the Floridan Aquifer System shows very little seasonal fluctuation in Lee County; however, seasonal variations over 15 feet occur in both the Sandstone and the mid-Hawthorn aquifers adjacent to major well fields (Wedderburn et. al., 1982). In wells with short casings, resulting exchange rates may as much as double during the dry season as compared with the wet season in these areas.

The theoretical extent of influence in a uniform flow field can be calculated given the exchange (injection) rate, the hydraulic conductivity, hydraulic gradient, and the thickness of the invaded aquifer. In the Buckingham area, the mid-Hawthorn aquifer was being contaminated by well number WA-181. The well was logged and an internal exchange rate of 55 gpm was measured with the well valved off. The saturated thickness of the mid-Hawthorn aquifer is 50 feet. A hydraulic gradient of two feet per mile and a transmissivity of 800 ft^2/day was determined from two nearby monitor wells. Assuming that the aquifer is homogeneous, isotropic, of infinite horizontal extent, and of constant thickness, the maximum width (W) of the saline plume generated down gradient of the well is calculated as (McWhorter and Sunada, 1981):

$$W = \frac{Q_w}{q_x b} \tag{16}$$

where Q_w is the injection rate (L^3), q_x is the Darcy velocity of the uniform flow in the invaded aquifer (L/t), and b is the saturated thickness of the aquifer (L). Using the values from well WA-181 the maximum theoretical width of the plume is 6.6 miles. The distance up gradient, where the flow rate from the well equals the existing flow rate of the invaded aquifer, is known as the stagnation point (S). This distance is calculated from the relation:

$$S = \frac{Q_w}{2\pi\ bq_x} \tag{17}$$

From the example above the distance to the stagnation point is over 5,500 feet.

In aquifers with higher hydraulic conductivities or steeper hydraulic gradients, the contaminant plume is less extensive. In the Biscayne aquifer in Dade County, a contaminant plume generated from a well flowing at a rate of

1000 gpm was mapped using surface geophysical methods (Figure 13). The hydaulic conductivity for the Biscayne aquifer at this location is approximately 8020 ft/day based on a thickness of 50 feet. The gradient is one third of a foot per mile. From this data, the width of the plume W is 7,700 feet and the distance to the stagnation point S is 1,200 feet. These values correlate well with the field data.

Solute transfer caused by the bulk movement of water through an aquifer is known as advection and represents the primary process in which a contaminant moves through an aquifer. The average velocity (V) of water through a porous medium can be expressed as the Darcy velocity (q_x) divided by the porosity ($\emptyset$):

$$V = \frac{q_x}{\emptyset} = \frac{-K\partial h}{\emptyset \partial s} \tag{18}$$

Where,

K = the hydraulic conductivity (L/t)

$\frac{\partial h}{\partial s}$ = the hydraulic gradient (dimensionless)

In the shallow artesian systems of Lee County, interstitial velocities are low. Using the data taken from well WA-181, and assuming a 10 percent porosity for the mid-Hawthorn aquifer, the average linear velocity is 0.065 ft/day. Applying this velocity to the distance to the stagnation point, the time needed for the contaminant to move down gradient of the injection well is 200 years. In contrast, groundwater velocities calculated from the Biscayne aquifer, where the hydralic conductivity is over two orders of magnitude larger than those of the mid-Hawthorn aquifer, were over one foot per day (Camp, Dresser, and McKee, 1980). Because other processes act to reduce the concentration of the contaminant as it moves from the source, consideration of advection alone represents the worst case calculation in terms of noticable water quality recovery.

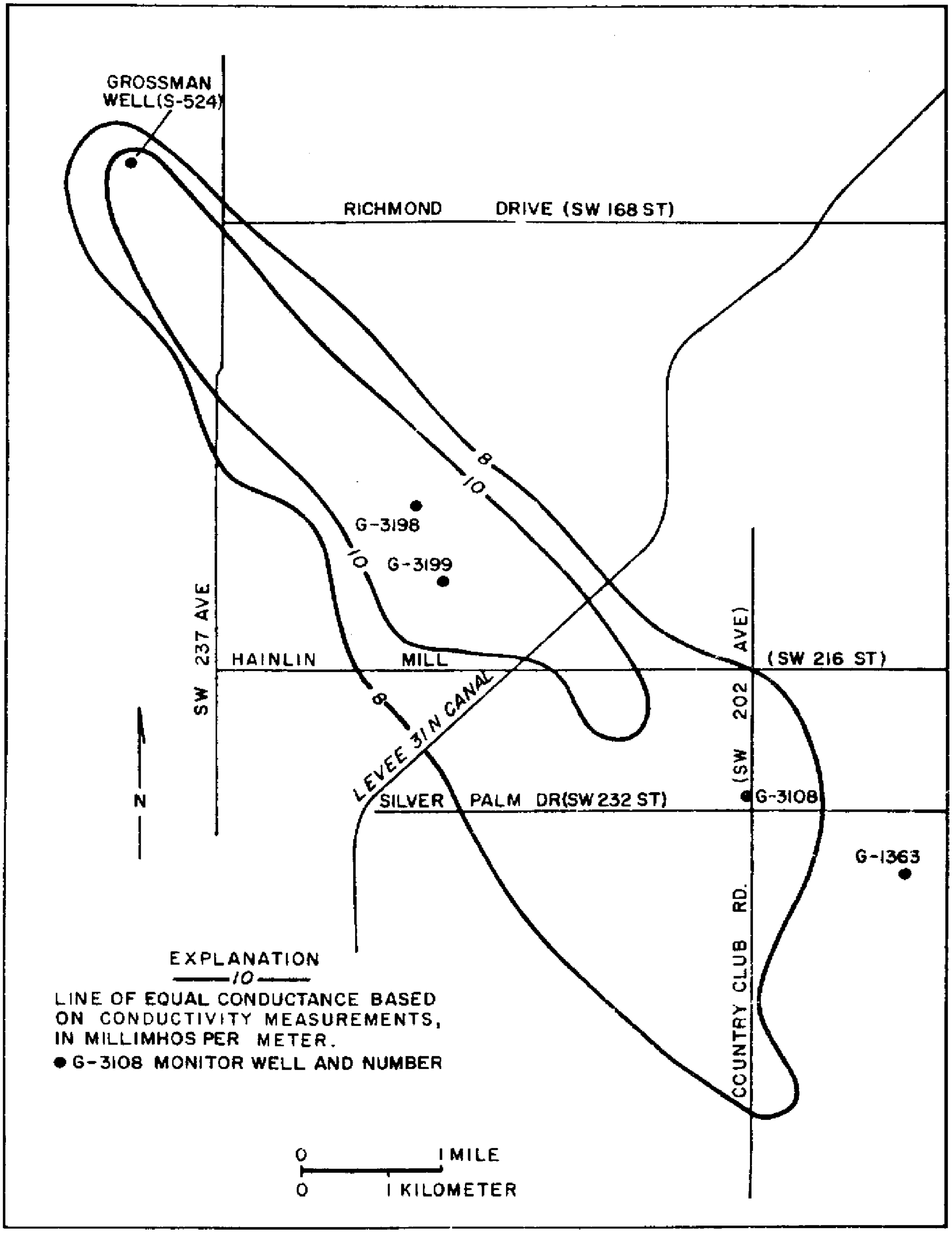


Figure No. 13 AREAL EXTENT OF A CONTAMINANT PLUME GENERATED BY THE GROSSMAN WELL IN DADE COUNTY, FLORIDA (FROM WALLER, 1982)

The primary process which acts to reduce saline concentration in a fractured environment is hydrodynamic dispersion. Dispersion refers to mixing caused by variations in interstitial velocities and molecular diffusion where,

$$D = f(v,d_1,d_2) + f(D_d) \qquad (19)$$

Dispersivity (D) is a function (f) of interstitial velocity (v), the longitudinal (d_1) and transverse (d_2) dispersivity coefficients, determined emperically, and molecular diffusion (D_d) (Mercer and Ross, 1982). The major factor which affects the values of v, d_1, and d_2 is media heterogeneity which cause variations in flow rates through the aquifer. In homogeneous particulate aquifers the effects of dispersion are small compared to the effects in the fractured and solutioned limestones which comprise the Sandstone and mid-Hawthorn aquifers of Lee County. Diffusion, which results through molecular motion, is primarily temperature dependent.

In confined aquifers dispersion occurs along the perimeter of the contaminant plume with the longitudinal dispersivity (parallel to the direction of flow) generally being larger than the transverse dispersivity. Water quality data from two monitoring wells in the mid-Hawthorn (LM-18 and LM-40) and one well in the Sandstone aquifer (LM-17) are shown in Figure 14. Contamination into the Sandstone aquifer occurred from a nearby well, WA-123, which was constructed with 80 feet of casing. Exchange rates between the Floridan and the Sandstone aquifer in WA-123 were below 20 gpm. The rapid recovery demonstrated in LM-18 and LM-40 is attributed to local development of the mid-Hawthorn aquifer. Increased gradients associated with pumpage act to increase interstitial velocities thus increasing the effective dispersivity of the mid-Hawthorn aquifer. In contrast, little development of the Sandstone aquifer occurs near the site and as a result of minor changes in the hydraulic

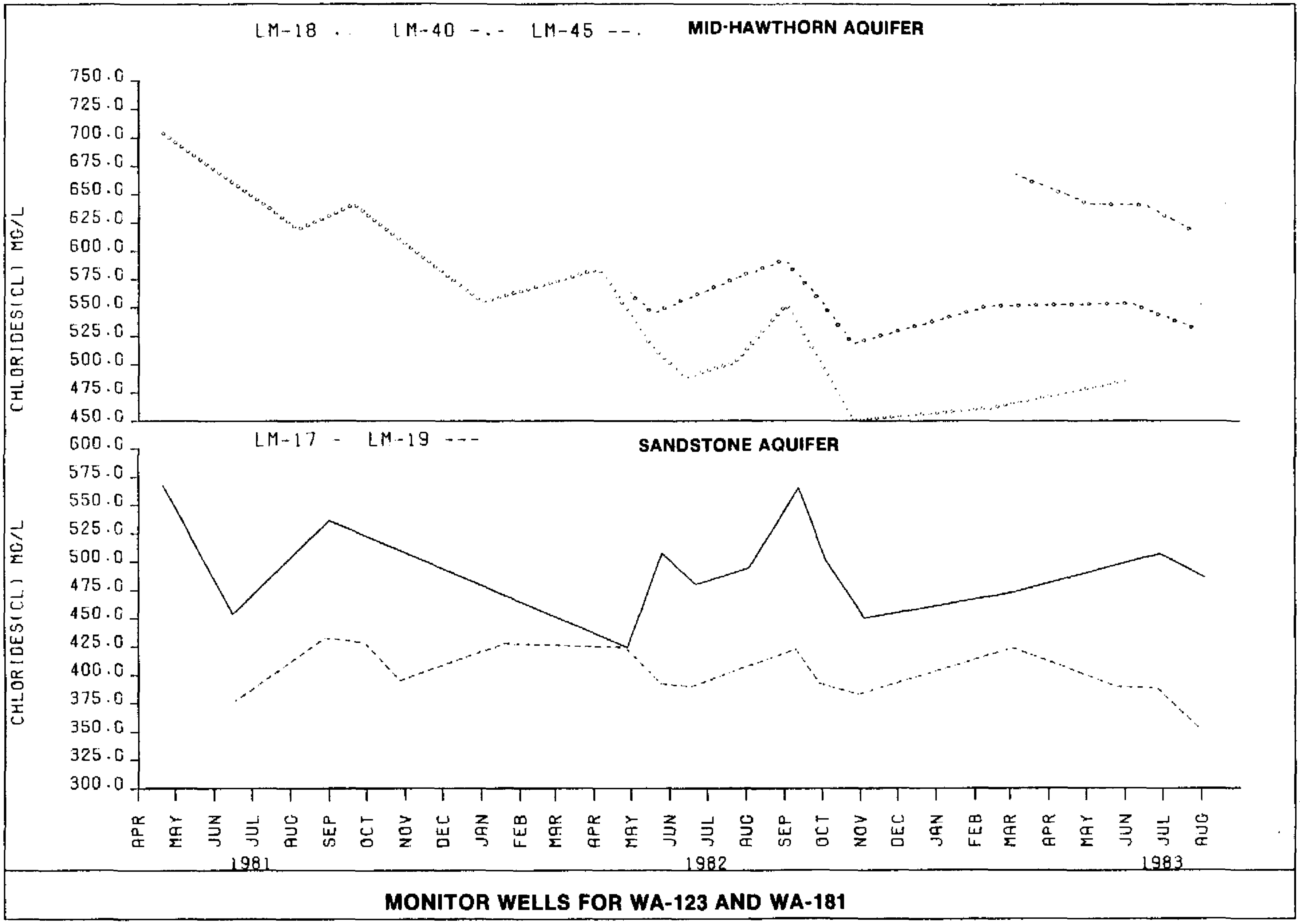


Figure No. 14 CHLORIDE DATA FROM MONITORING WELLS IN THE SANDSTONE AND MID-HAWTHORN AQUIFER NEAR WA-123 AND WA-181

gradient, recovery is more gradual. Preliminary data indicate that recovery rates for the shallow artesian aquifers depend primarily on the extent of contamination and the degree to which the aquifer is developed after the contamination is stopped. Based on the theoretical extent of contamination caused by even small inter-aquifer exchange rates, combined with low hydraulic conductivities, hydraulic gradients, and recharge rates for both the mid-Hawthorn and the Sandstone aquifers, significant water quality recovery generally occurs on the order of several years after plugging.

Dispersion in unconfined aquifers is accelerated by direct recharge. The lower density fresh water effectively "floats" on top of saline water allowing dispersion to occur vertically as well as horizontally about the contaminant plume. Additional characteristics of water table aquifers which act to accelerate water quality recovery include rapid changes in hydraulic gradients associated with convective storms, and seasonal temperature variations which influence diffusion rates.

An example of water quality recovery in the water table aquifer was presented by Boggess (1973) in the Bonita Springs area of Lee County. A saline plume over 600 feet down gradient from a deep well flowing five gpm was identified in the Highland Estates development. Four shallow residential wells within the plume were monitored for a period of four years. Three months after the deep well was plugged, chloride levels in the monitor wells dropped an average of 60 percent (Figure 15). By October 1969, 20 months after plugging, the chloride levels in the four monitor wells had virtually reached background levels. Representative rainfall data for the period was taken from Corkscrew Swamp, approximately 8 miles east of the study. The uniform recovery observed at all stations suggests that dilution of the plume by rainfall is more prevalent than dissipation by advection. If this is the case, similar rapid recovery rates can be anticipated for larger plumes

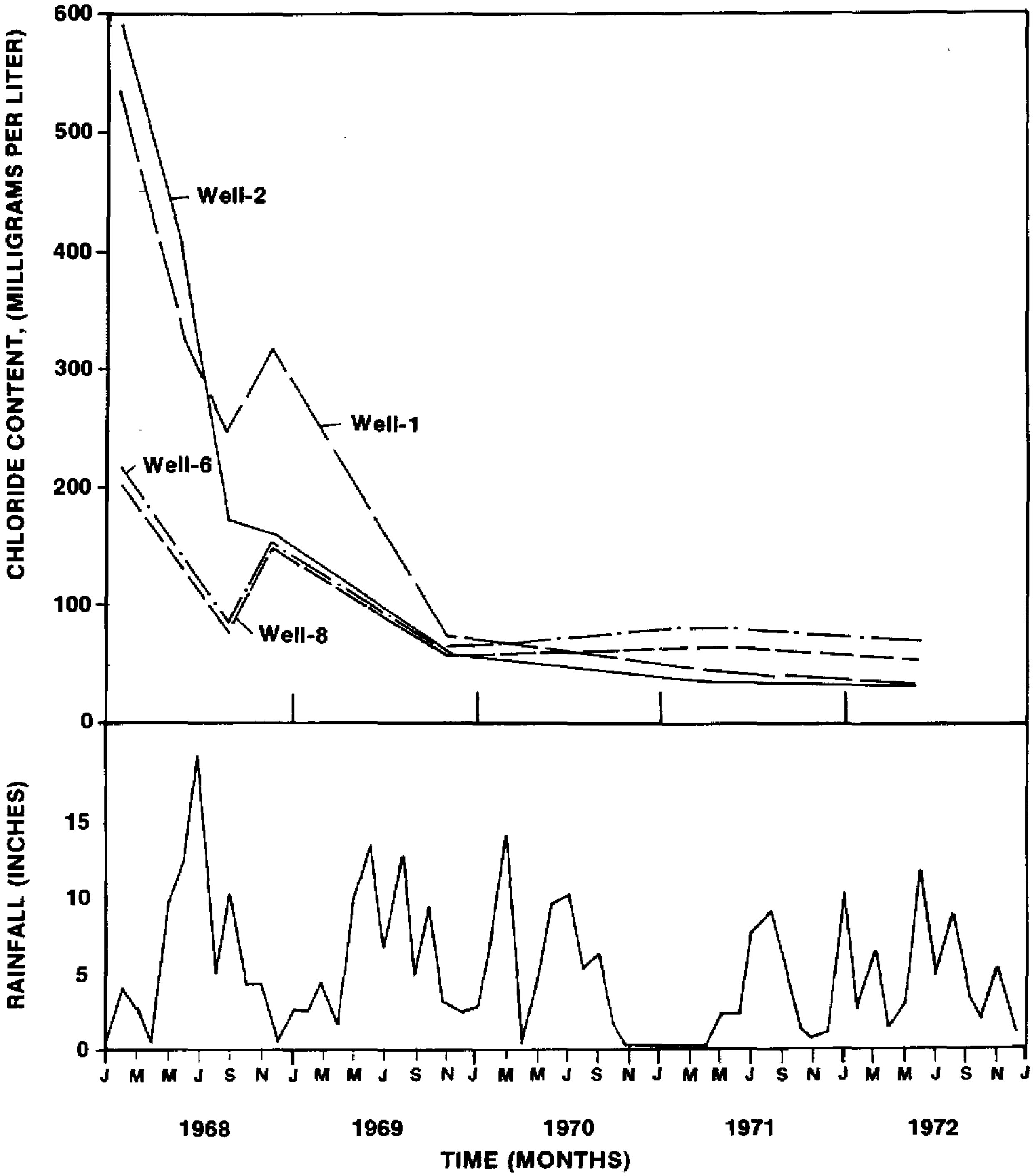


Figure No. 15 RELATION BETWEEN RAINFALL AND GROUNDWATER RECOVERY IN AN UNCONFINED AQUIFER IN BONITA SPRINGS (MODIFIED FROM BOGGESS, 1973)

providing they occur in permeable surficial sediments which are exposed to frequent rainfall. Based on this, significant dissipation of a contaminated plume in the water table aquifer of Lee County can be expected to occur within one year.

The effects of plugging free flowing wells is reflected in the regional potentiometric surface of the Floridan Aquifer System in Lee County. Boggess (1974) examined variations in the potentiometric levels of the Floridan Aquifer System using data collected between 1944-1950 and 1966-1973. The data collected from 1966 to 1973 showed a significant depression in the equipotential lines adjacent to the Caloosahatchee River which was attributed to "discharge and leakage from the large concentration of artesian wells along the river". Potentiometric data was collected in 1983 and compared to the 1974 data as shown on Figure 16. The eastward migration of the 50 foot contour reflects the increased withdrawals from the Floridan Aquifer System by the citrus industry in northeastern Lee County and Hendry County. However, from Ft. Myers south along the Caloosahatchee River where plugging efforts have been concentrated, an increase in artesian pressure is observed. This is mainly demonstrated by the straightening of the 30 foot contour. The depression in western Cape Coral corresponds to the reverse osmosis plant which uses water from the Floridan for municipal supply. Several wells monitored in Iona have shown increases in potentiometric levels up to five feet in one year and appear to be related to well plugging activities. Potentiometric data was collected prior to the plugging of a number of wells in the City of Ft. Myers. The deep well inventory provided by the USGS indicates the highest concentration of surveyed wells occurs within the City of Ft. Myers. As the City of Ft. Myers joined the plugging program in 1982, only a small percentage of the wells in that area have been plugged. It is anticipated that continued plugging efforts within the City limits will result in increases in the potentiometric surface in this area also.

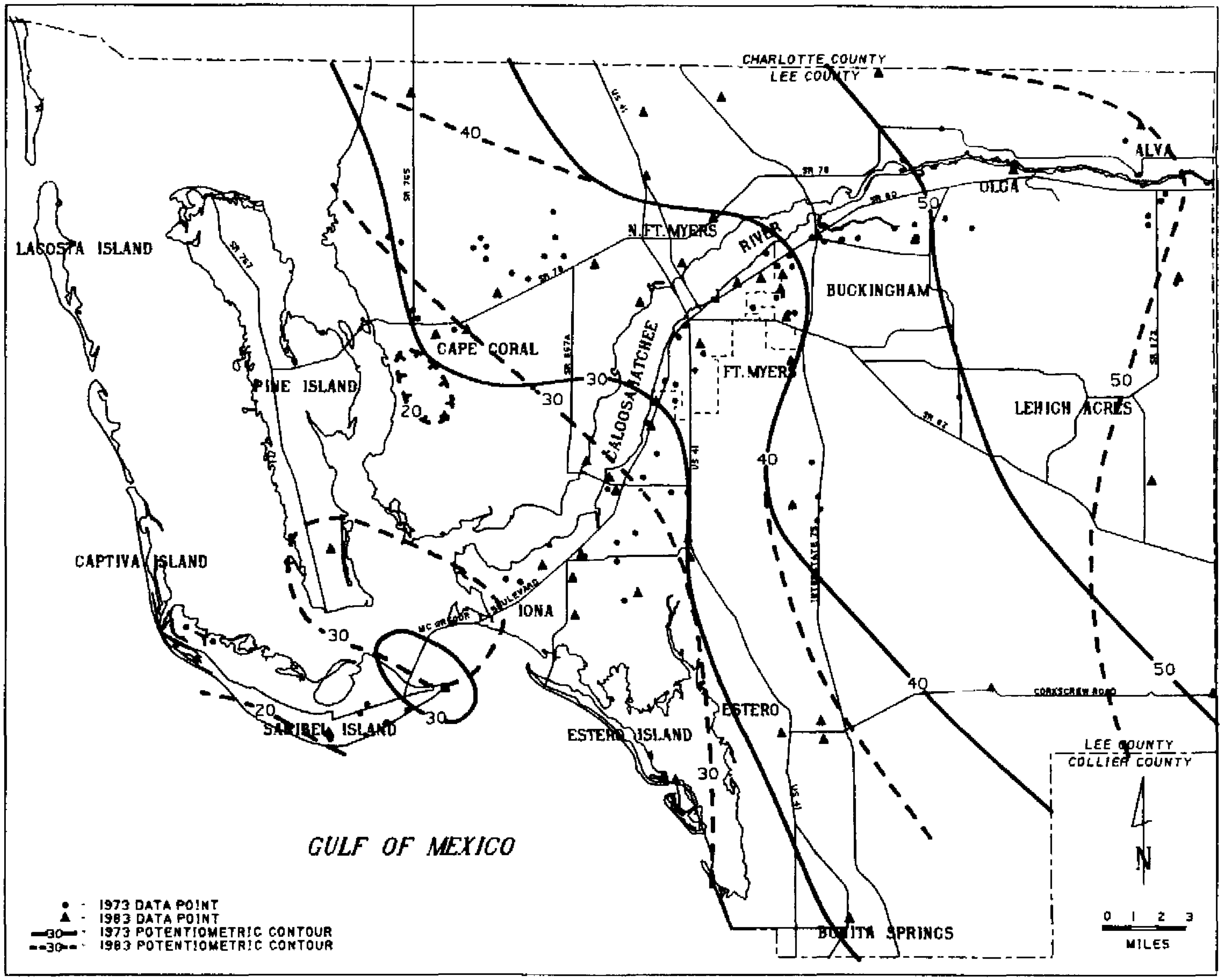


Figure No. 16 VARIATIONS IN THE POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER SYSTEM BETWEEN 1973 AND 1983 (MODIFIED FROM BOGGESS, 1974)

RECOMMENDATIONS

1. Further investigations into the life expectancy of steel casings should be undertaken with respect to regulating wells currently exempt from requirements of cement grouting (cable tool drilling with driven casings).
2. Detailed investigations pertaining to the occurrence of structural offset beds in pre-Miocene sediments should be undertaken prior to consideration of deep well injection sites in Lee County. Such investigations should conclusively define the nature of the offsets (faulting of folding) as well as establishing their vertical and areal extent.
3. Funding should be provided to develop and institute remote sensing techniques such as thermal infrared photo imagery to locate free flowing wells in remote areas.
4. Data collection from existing water quality monitoring networks should be continued to further quantify the recovery rates. Additional monitoring should be established in areas where plugging activities have been maximized. Applications of surface geophysical methods should be examined as an inexpensive method of monitoring the location and dissipation of saline contamination in shallow aquifers.
5. This type of program is beneficial to groundwater resources and should be expanded to other counties in the District. Funding should be substantially subsidized by the land owners, municipal governments, or state agencies on a cooperative basis. As hydrogeologic conditions vary throughout the District, site specific geophysical data should continue to be obtained to provide the basis for plugging designs.
6. The South Florida Water Management District should encourage county governments to draft zoning ordinances which require the appraisal and plugging of all flowing wells on properties prior to zoning changes and/or development.

7. County governments should be encouraged to develop inventories of free flowing wells within their boundaries. These inventories should be prioritized to achieve maximum benefit from limited budgeting. Wells should be categorized on the basis of discharge rate, salinity, degree of maintenance and proximity to municipal wellfields or potable sources.

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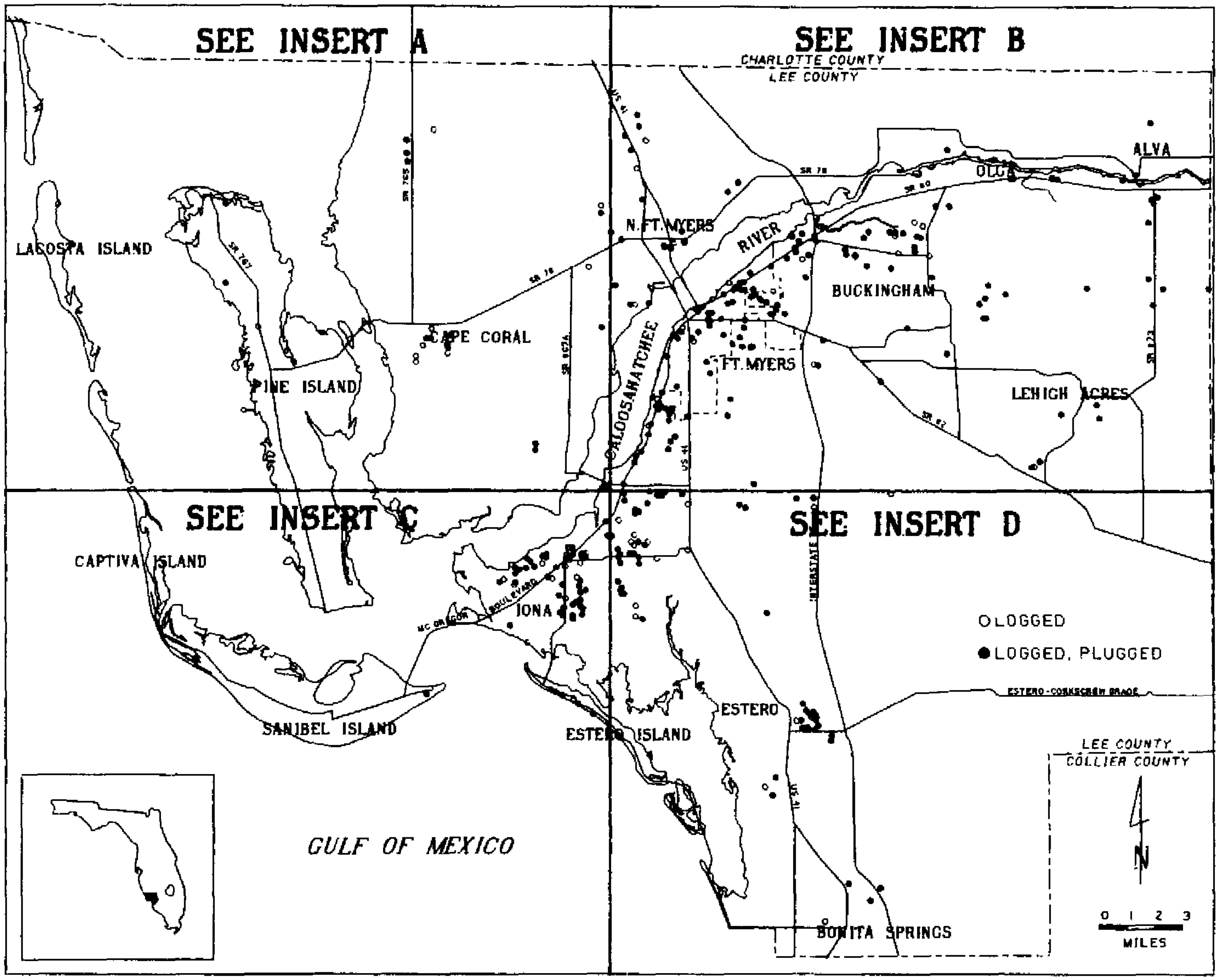
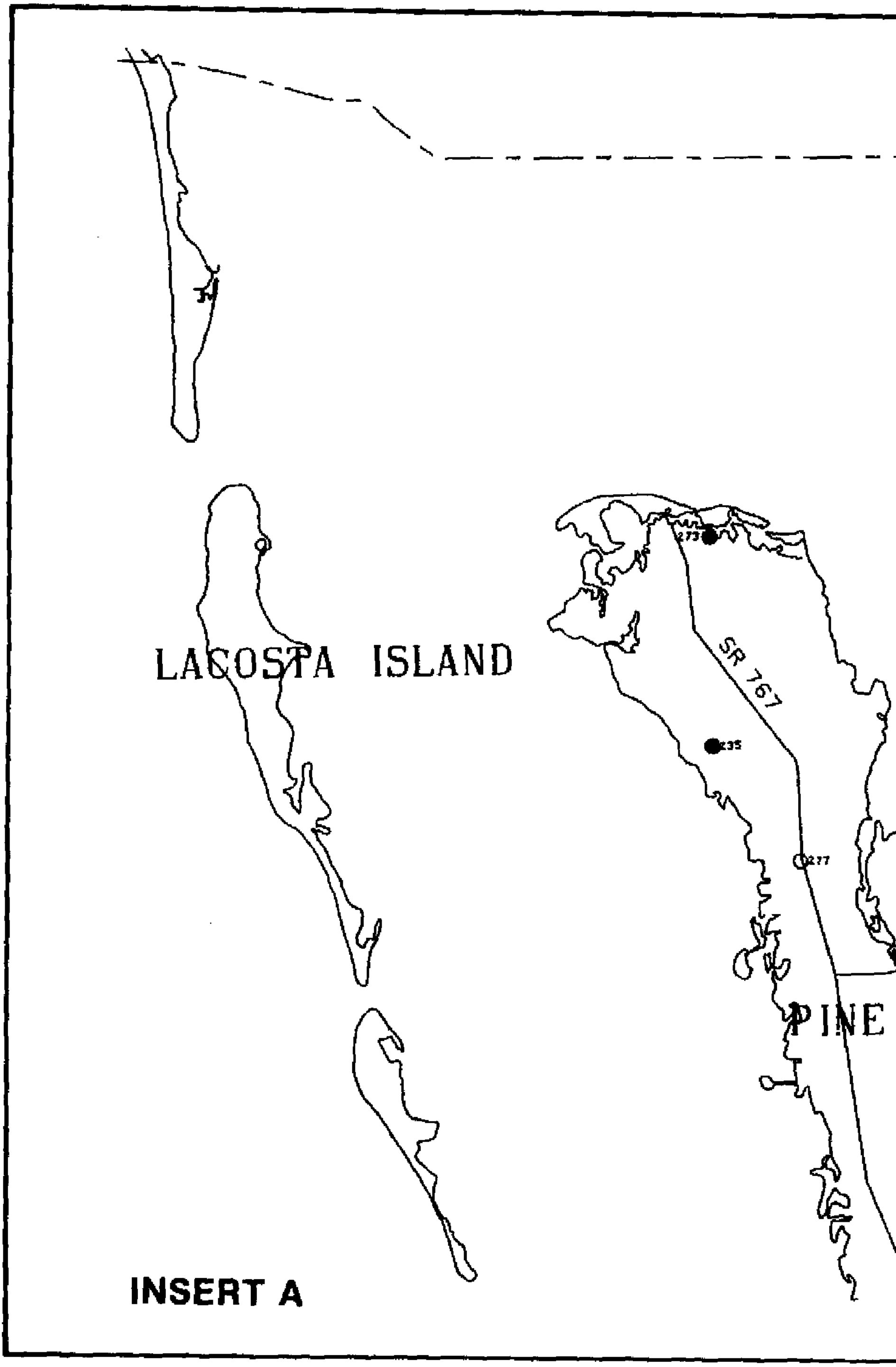
APPENDIX I

Well Locations and Selected Data From the South Florida Water Management District's Deep Well Plugging Program



LOCATION OF WELLS SURVEYED AND PLUGGED IN THE SFWMD'S DEEP WELL PLUGGING PROGRAM FROM 1979 TO 1983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PINE
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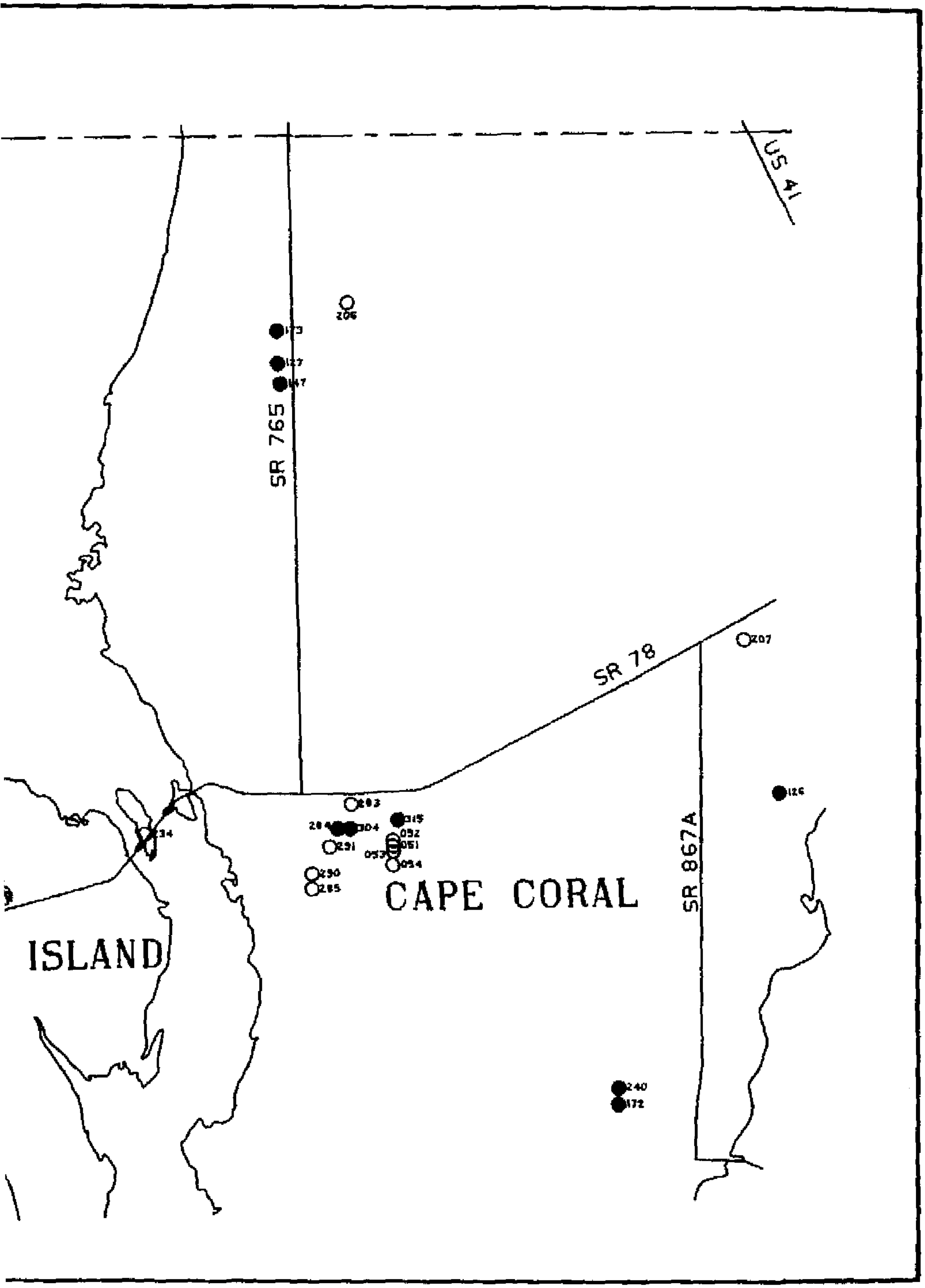
US 41
SR 765
SR 78
SR 867A
CAPE CORAL
ISLAND
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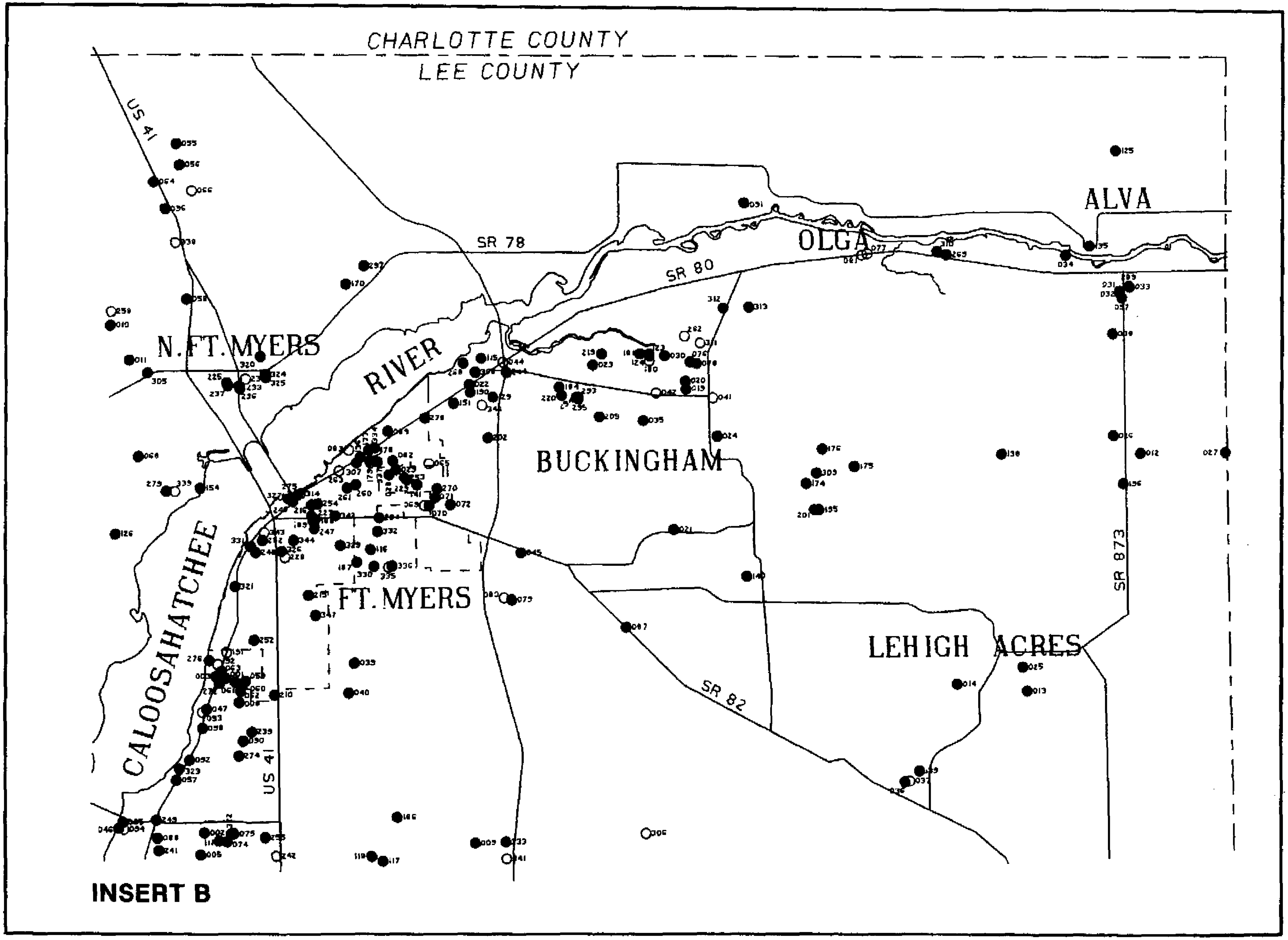
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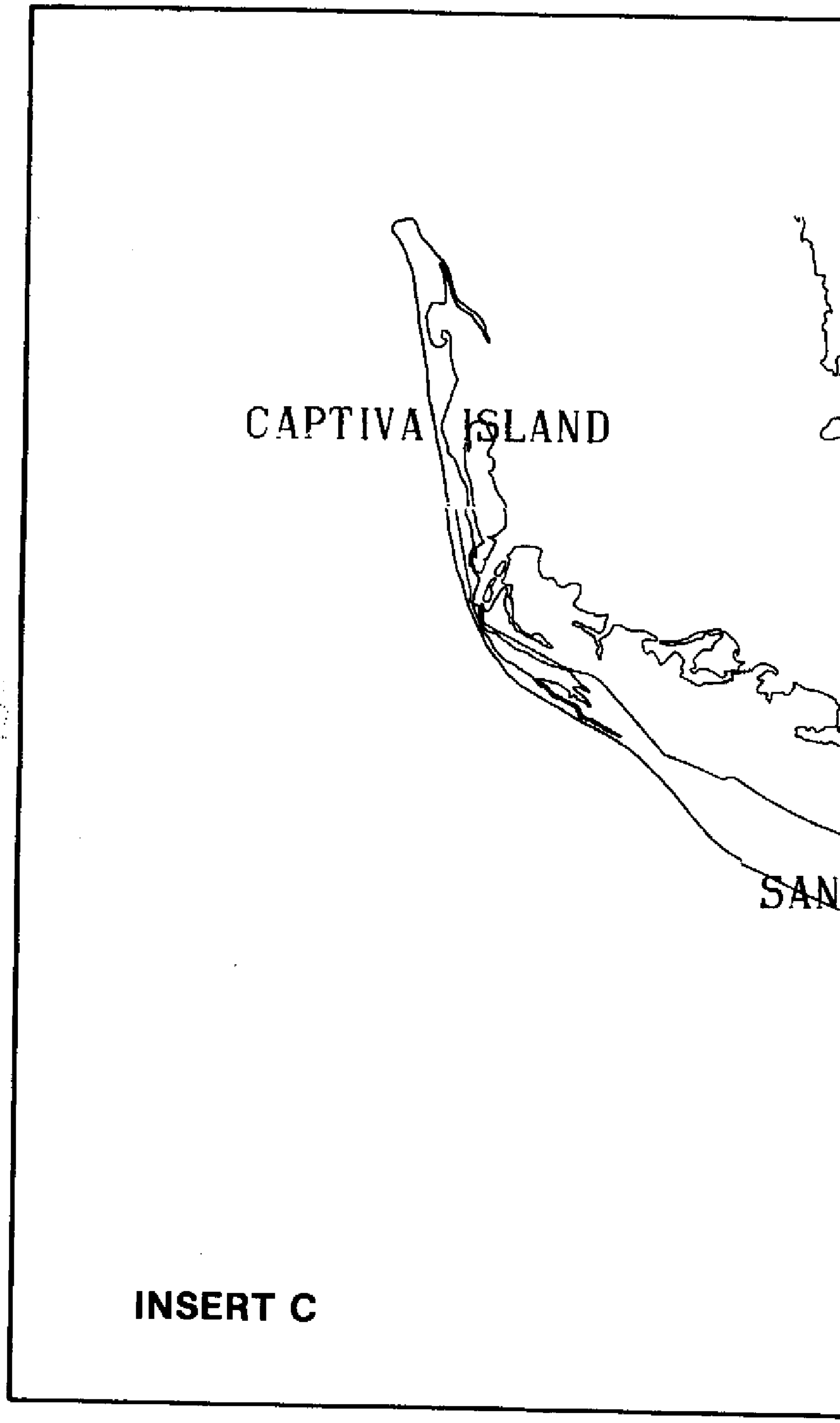
LEE COUNTY
US 41
SR 78
SR 80
N. FT. MYERS
RIVER
OLGA
ALVA
BUCKINGHAM
CALOOSAHATCHEE
FT. MYERS
SR 82
SR 873
LEHIGH ACRES

INSERT B



CAPTIVA ISLAND
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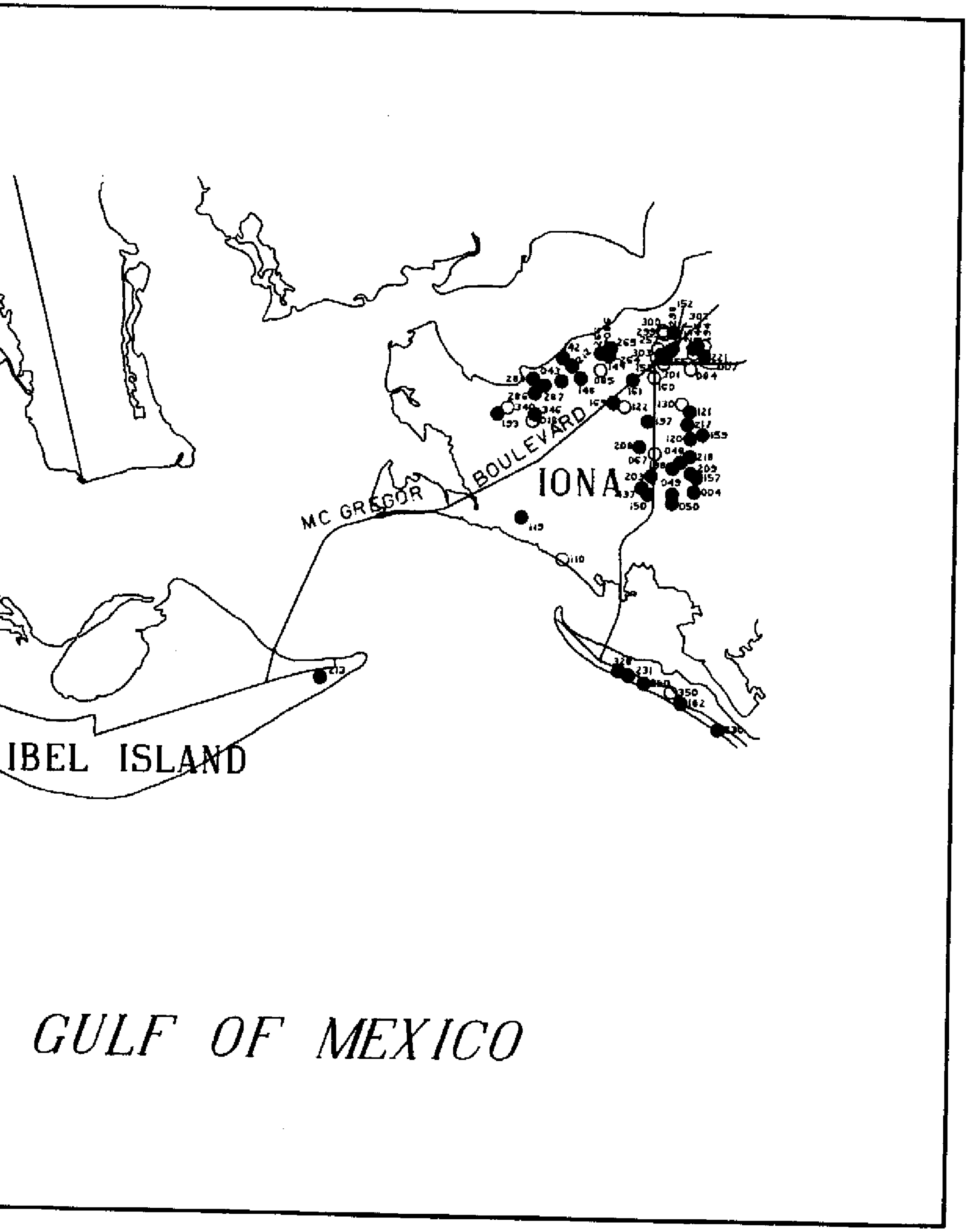
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IONA
IBEL ISLAND
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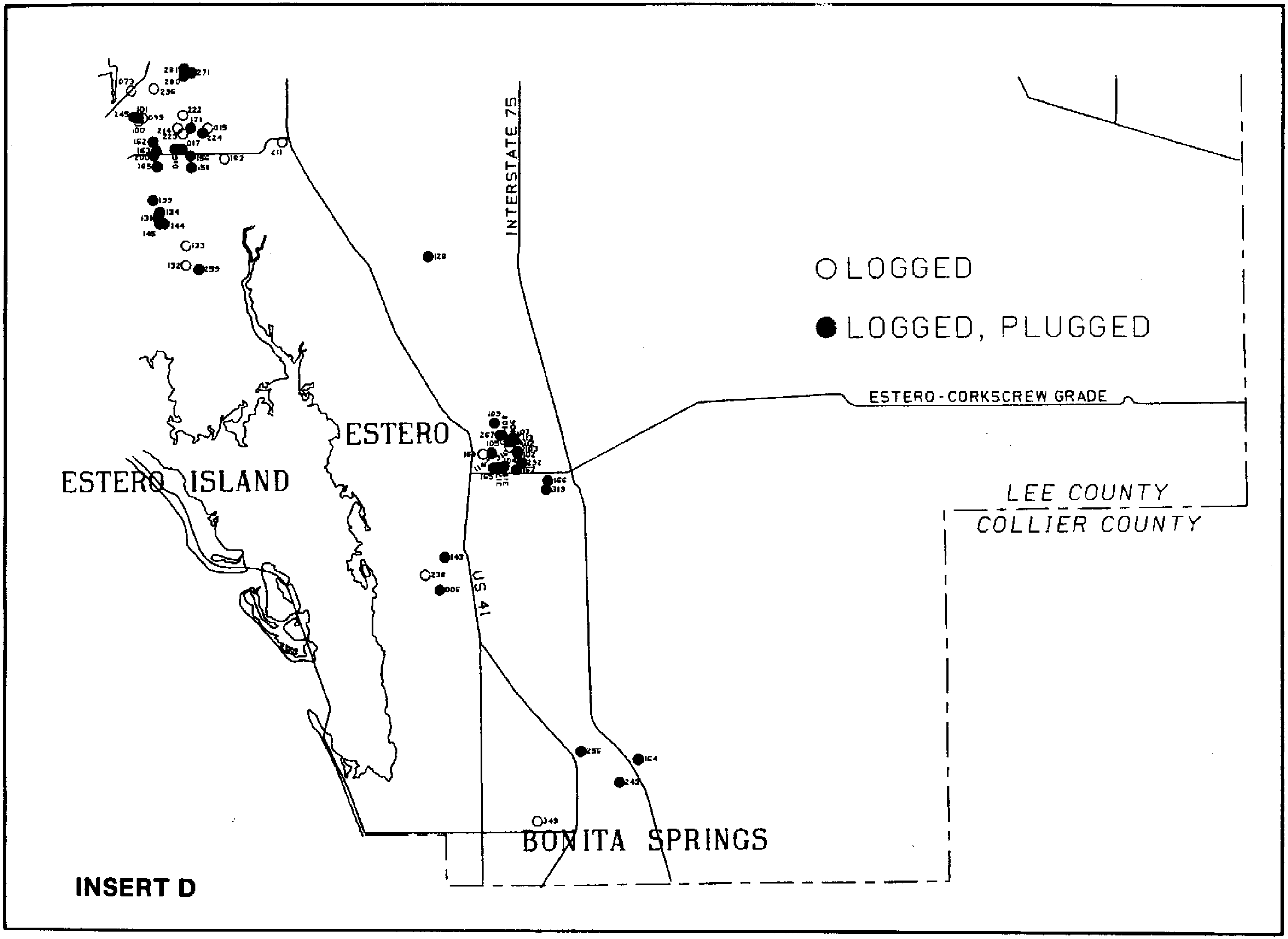
INTERSTATE 75
LOGGED
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ESTERO-CORKSCREW GRADE
ESTERO
ESTERO ISLAND
LEE COUNTY
COLLIER COUNTY
US 41
BONITA SPRINGS
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